Integration and Control of Morphing Wing Structures for Fuel Efficiency/Performance

NARI's ARMD 2011 Phase 1 Seedling Fund Technical Seminar
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Pressure Adaptive Structures for Distributed Control of Morphing Wing Vehicles

- Project Overview
  - Objectives
  - Background
  - Challenges
  - Concepts: PAHS and DMoWCs
  - Infusion path
  - Approach
  - Phase 1 Status
- Technical Details and Accomplishments
  - Part 1: Pressure adaptive honeycomb
  - Part 2: Distributed decentralized control
  - Part 3: Small-scale morphing wing prototype study
- Summary

Pressure Adaptive Structures for Distributed Control of Morphing Wing Vehicles

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- Objective
  - Investigate GN&C of vehicles through distributed morphing wing shape control using pressure adaptive honeycomb structures (PAHS) towards drag reduction, increased efficiency, and enhanced capabilities.
  - Airfoil shape morphing to replace traditional control surface actuators
  - Distributed system of smart actuators (locally-sensing, locally-affecting, autonomous and multifunctional)
  - Combine classical modeling/control approaches with massively paralleled computing capability
- Innovation
  - Concept of Pressure Adaptive Wing System (PAWS) studies two novel approaches:
  - Pressure Adaptive Honeycomb (**PAHS**) morphing structures
  - Distributed and decentralized flight control through a Distributed Morphing Wing Control System (**DMoWCs**)
  - Studies replacing flight control surface actuation with intelligent distributed morphing
- Ties into NASA Aeronautics goals
  - Enabling lighter-weight multifunctional wing structures
  - Reduced drag and increased efficiency
  - Mission and configuration adaptation
  - Increased safety and robustness

Distributed Control through Pressure Adaptive Structures

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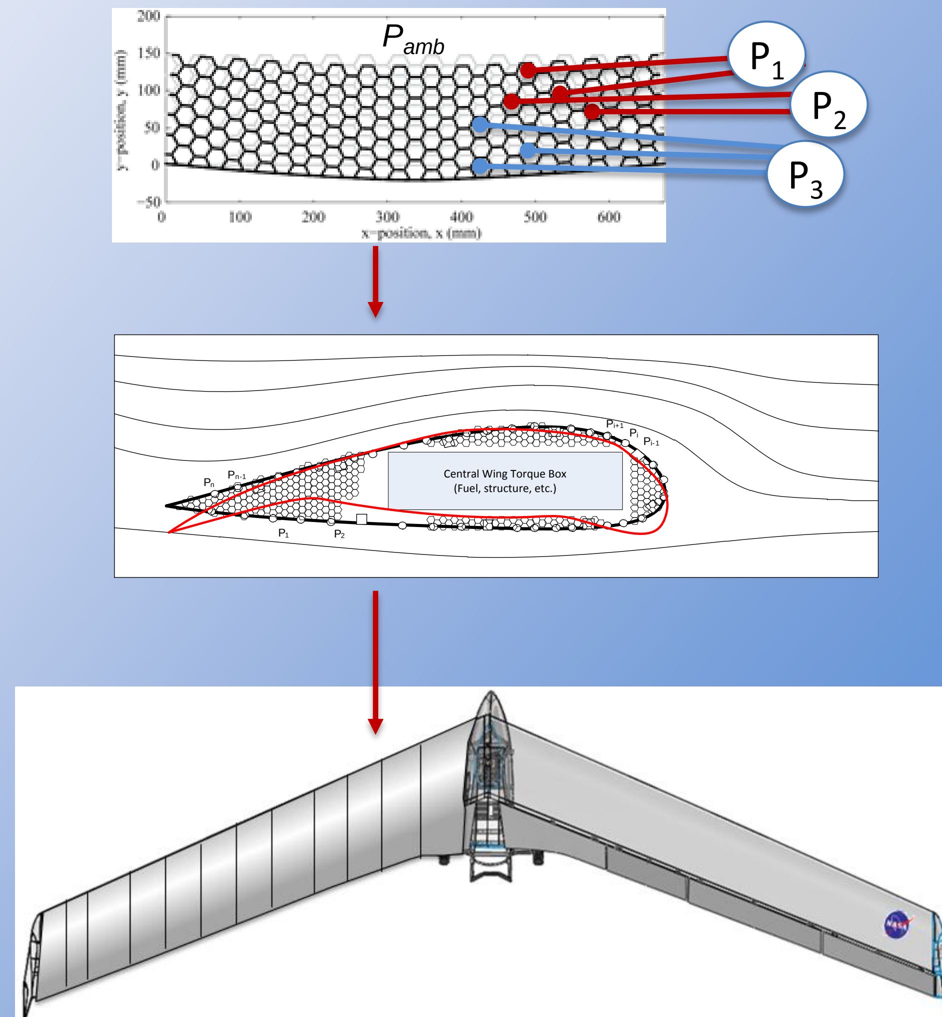
- Pressurized honeycomb structure with active/passive bladders
- Install in the wing in place of standard control surface actuators to affect wing shape change
  - Adaptive intrados/extrados wing surfaces, trailing and leading edge deflection
- Control sections independently for vehicle flight guidance and control
- Distribute and decentralize control authority to local sections (architecture) – smart sensing, distributed control intelligent, actuation autonomy
- Blend rigorous control techniques with modern massively-paralleled many-core technology



History and Benefits

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- Long history of morphing wing research since 1920 (at least)
  - Parker's variable camber wing (Parker, 1920), NASA Aeroelastic Active Wing (1990's), Supercritical Mission Adaptive Wing (Powers, 1997), NASA Morphing Aircraft Program (Wlezien, 1998), DARPA/AFRL/NASA Smart Wing Project (Kudva, 2004), …
  - Many recent surveys (Barbino 2011, Sofla 2010, Reich 2007, Kudva 2004,…)
  - Studies for distributed local shape actuation concepts in terms of aerodynamic-effect and feasibility, showing increase of benefits over global actuation
  - Studies show numerous benefits to actively controlling wing shape throughout the mission/flight regime

Benefits includes…

... increased aerodynamic efficiency, drag reduction and enhanced lift-to-drag performance, enhanced maneuverability, reduced fuel consumption, increased actuator effectiveness, decreased actuator power requirements, increased control robustness, control redundancy, shorter required takeoff/landing length, flutter and stall mitigation, reduced airframe noise, increased stability and reduced stall susceptibility, …

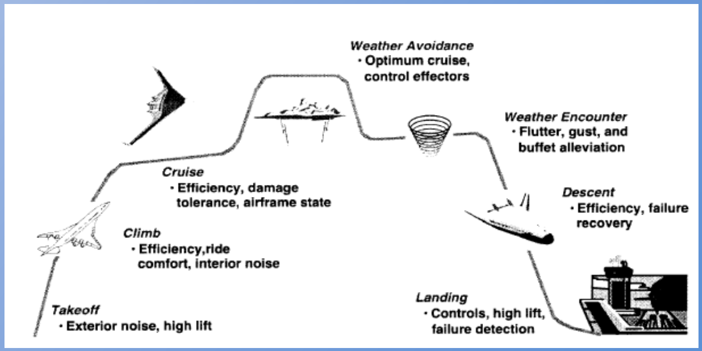

Figure: Application of shape morphing technology (Wlezien, 1998)

Challenges and Needs

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- Actuation materials and scaling of mechanisms
  - Challenges in scaling of small laboratory or small-vehicle mechanism concepts
  - Challenges in materials certification
  - PAHS modeling (kinematics, dynamics)
  - Controlling shapes through PAHS
  - Optimization for multi-objective, multi-constrained flight control
  - Design models and system-level tradeoffs (MDAO)
- Distributed morphing control challenges
  - Need to show that decentralized shape control is feasible and promising
  - Many advanced large-scale nonlinear control concepts are difficult to validate
  - Lack of adequate models for control development for distributed concepts
  - Lack of control systems-level integration studies, integrating distributed morphing as primary actuator into a flight control system
  - Lack of system-level vehicle integration data/models for designers or for including into an design/MDAO process

Pressure Adaptive Honeycomb

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- Pressure Adaptive Honeycomb Structures (PAHS)
  - PAHS actuation has been demonstrated on small scale lab tests
  - Shown to have favorable characteristics in comparison to other types of morphing actuation (such as SMA's, piezoelectric)
  - Potential for distributed control
  - Complexity in application – structural design, kinematics/dynamics that describe actuation input to shape, multiple inputs
  - Need models for shape control, need larger-scale prototype for validation of initial study
- Apparent Benefits (from small-scale prototype)
  - Enabling lighter-weight multifunctional wing structures
  - Capable of "huge" (50+%?) strains
  - Fully proportional, easily controlled
  - Stiff & strong enough to handle "real" loads
  - Lighter than conventional aircraft actuation systems
  - Faster than conventional aircraft actuation systems
  - Less costly than conventional aircraft actuation systems
  - Does note require dedicated power system/consumption
  - Self-diagnostic with self-repair capability
  - Certifiable under FAR 23/25, 27/29

Vos, Barrett. "Topology Optimization of Pressure Adaptive Honeycomb for a Morphing Flap", SPIE Smart Structures, San Diego, CA. March 2011

PAHS Compared to Adaptive Materials

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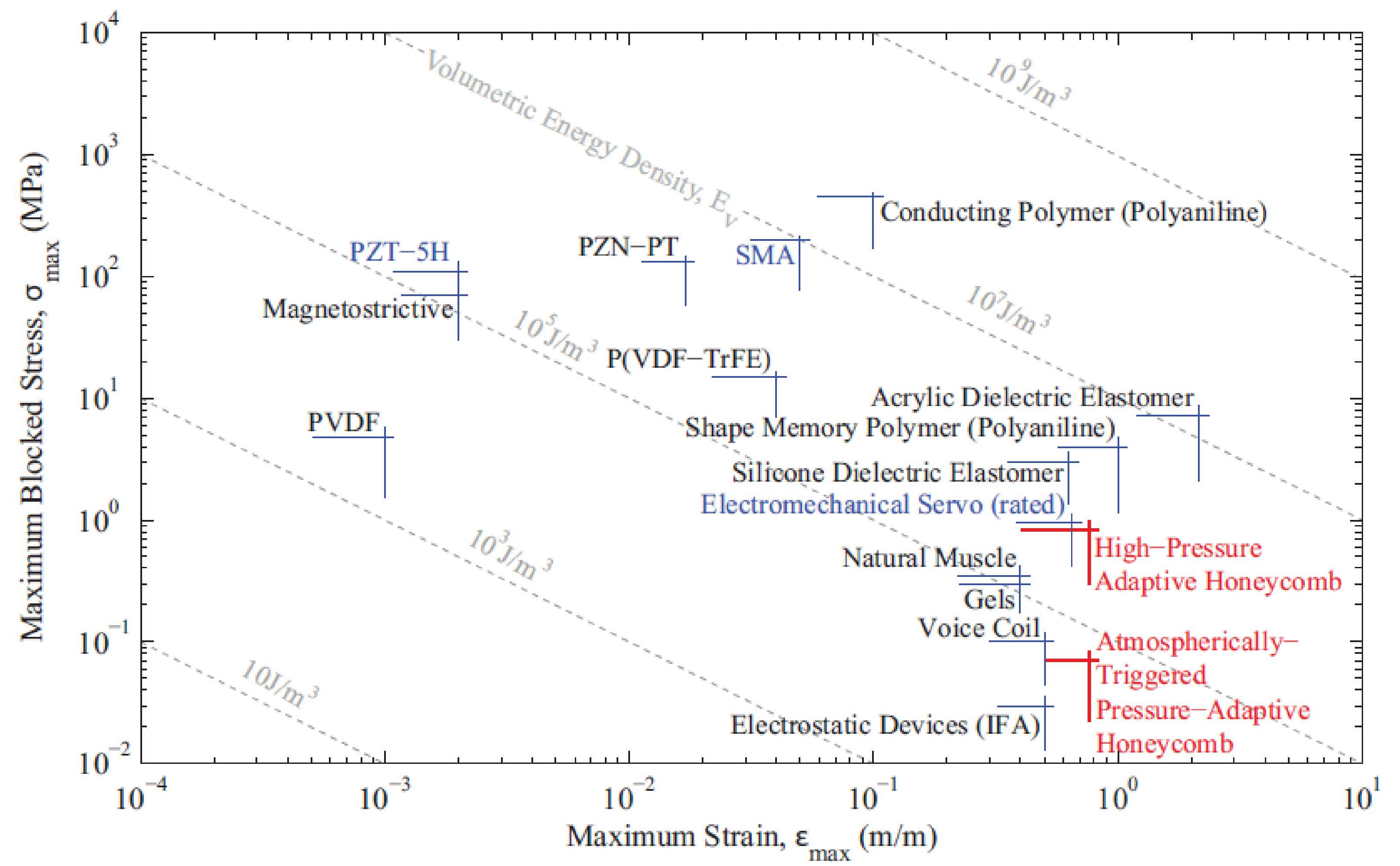

Based on initial study of laboratory prototype

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PAHS Compared to Adaptive Materials

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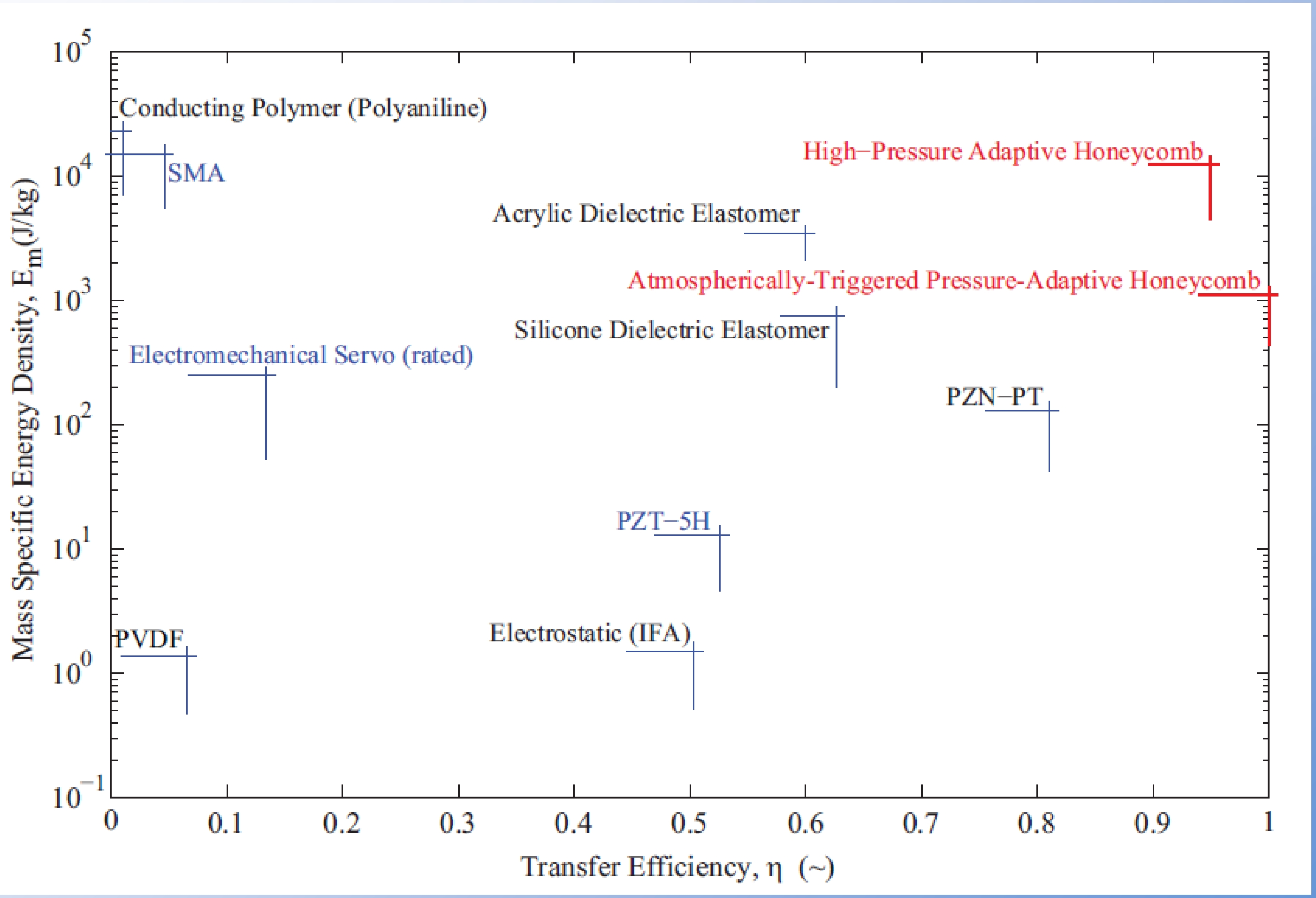

Based on initial study of laboratory prototype

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Challenges with Traditional Flight Control Modeling and Design

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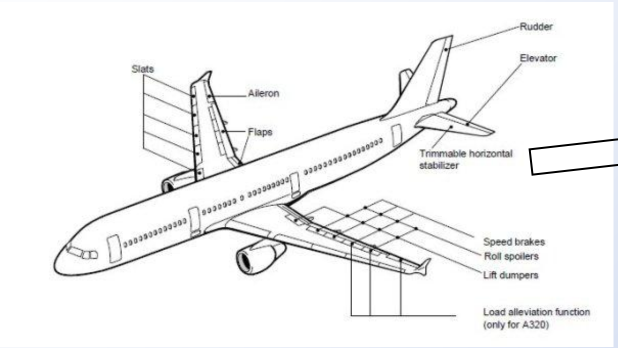
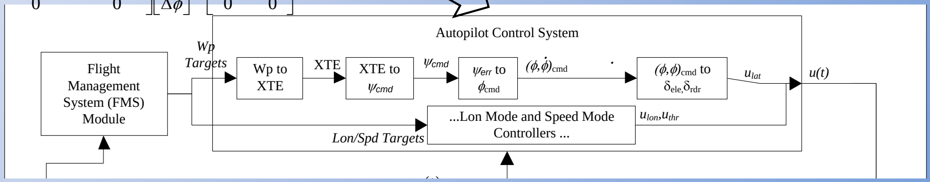
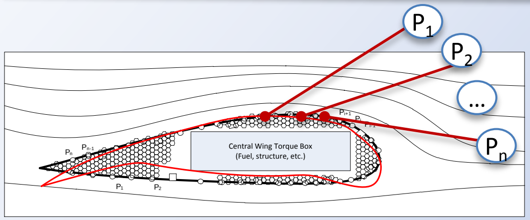


Simply, linearize, assume, simplify some more until a simple input-output mapping is derived
Valid for only small 'deviations' around trim state
Linearize around as many trim-states as possible
Make system look like a simple spring-mass-damper (bypasses fluid response)

$$\frac{d}{dt}\begin{bmatrix}\Delta v\\ \Delta p\\ \Delta r\\ \Delta\phi\end{bmatrix}=\begin{bmatrix}Y_v & Y_p & -(u_0-Y_r) & g\cos\theta_0\\ L_v & L_p & L_r & 0\\ N_v & N_p & N_r & 0\\ 0 & 1 & 0 & 0\end{bmatrix}\begin{bmatrix}\Delta v\\ \Delta p\\ \Delta r\\ \Delta\phi\end{bmatrix}+\begin{bmatrix}0 & Y_{\delta r}\\ L_{\delta a} & L_{\delta r}\\ N_{\delta a} & N_{\delta r}\\ 0 & 0\end{bmatrix}\begin{bmatrix}\Delta\delta_a\\ \Delta\delta_r\end{bmatrix}$$

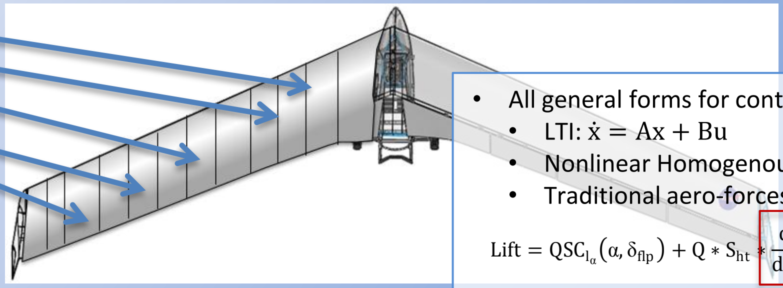


Control largely SISO loop-at-a-time cascades, indicative of classical control



Distributed shape changing concept

... or any distributed local actuation concept



- All general forms for control modeling are not satisfactory, eg.
  - LTI: $\dot{x} = Ax + Bu$
  - Nonlinear Homogenous Form: $\dot{x} = fH(x,t) + fF(u,t)$
  - Traditional aero-forces/moment build up, eg:

$$\text{Lift} = QSC_{l_\alpha}(\alpha, \delta_{flp}) + Q * S_{ht} * \boxed{\frac{dC_l}{d\delta_{ele}}}\delta_{ele} + \left(\frac{QS\bar{c}}{2V}\right)\frac{dC_l}{d\dot{\alpha}}\dot{\alpha} + \left(\frac{QS\bar{c}}{2V}\right) * \frac{dC_l}{dq}q \ \ldots$$

- Fundamentally a large-scale problem
- Nonlinearity, non-symmetry
- Complex actuation and dynamic coupling
- Large set of control inputs, large number of states
- Homogenous time-variance
- Fluid response cannot be simplified out of equations

Decentralized Control Approach and Impact

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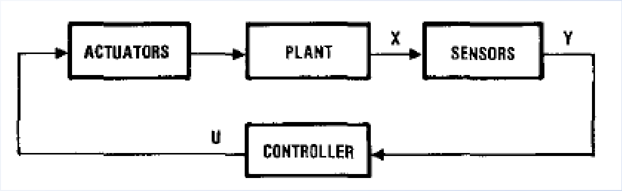
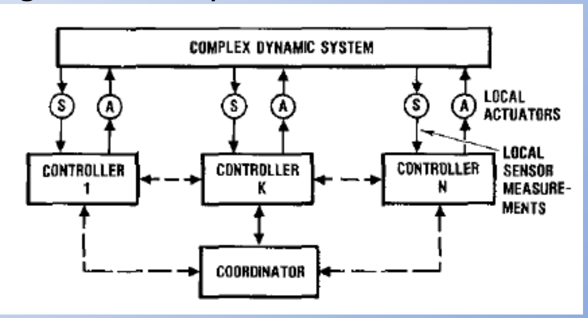
- DMoWCs : Distributed Morphing Wing Control System
  - Novel control approach for design of distributed flight control systems





Centralized Versus Decentralized (Sesak & Coradetti 1979)

  - Scalable massively parallelizable framework for multi-objective constrained optimization
  - Modeling and controlling spatially-invariant large-scale dynamic systems
  - Distribution and decentralization using local controllers/sensors/actuators
  - Incorporates into existing flight control architectures
  - Can be verified using classical control techniques and metrics
  - Proposed large-scale control-modeling approach applicable to any distributed actuator systems, captures nonlinearity, complexity, large-scale effects
  - General framework for distributed heterogeneous smart-actuator control of large-scale systems
  - Applying same architecture for research for smart-building control system research (NASA ARC Sustainability Base)

Infusion Path to NASA ARMD Program

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- Phase 1 results show the approaches to both morphing and control are feasible
- Found support from partners in NASA and industry
  - Letter of support from NASA ARMD FW's ESAC (Elastically Shaped Aircraft Concept) task
  - Letter of support from Boeing Company, Research and Technology business unit
  - Letter of support from Cessna Aircraft Company, Co-PI from MLB company (UAV market)
- Infusion Path
  - Overall phase 2 goal is to advance the concept maturity to be incorporated into existing NASA projects and industry
  - Tests PAWS actuator at larger scale, applying DMoWCs in demonstration
  - Phase 2 will provide NASA/Boeing teams with regular updates, get regular feedback
- Benefits for NASA project
  - Actuator deliverables provides ESAC/Boeing project with new actuation possibility
  - Control models and framework provides new approaches to ESAC
  - Framework could allow ESAC to approach other NASA projects in related disciplines (eg smart-material projects) for collaboration

Approach and Initial Plan

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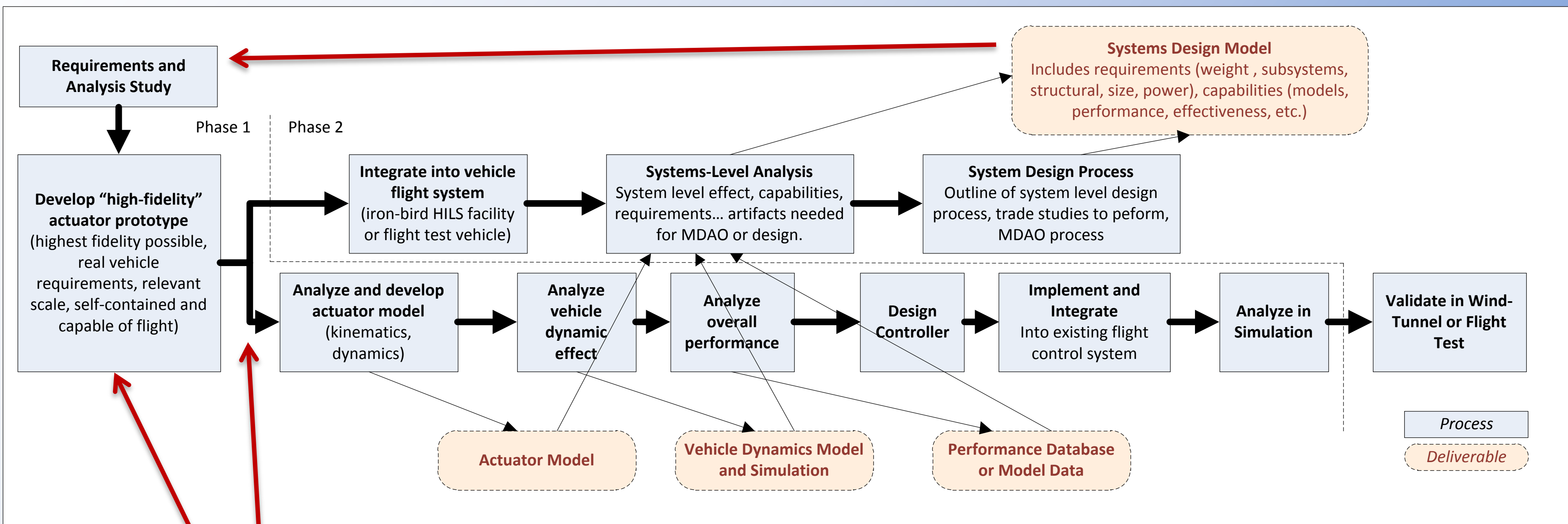

1. Task plan dependency issue
2. Prototype requirements issue (what to build, effectiveness of flight testing without 'going through the loop' again)

Approach and Modified Plan

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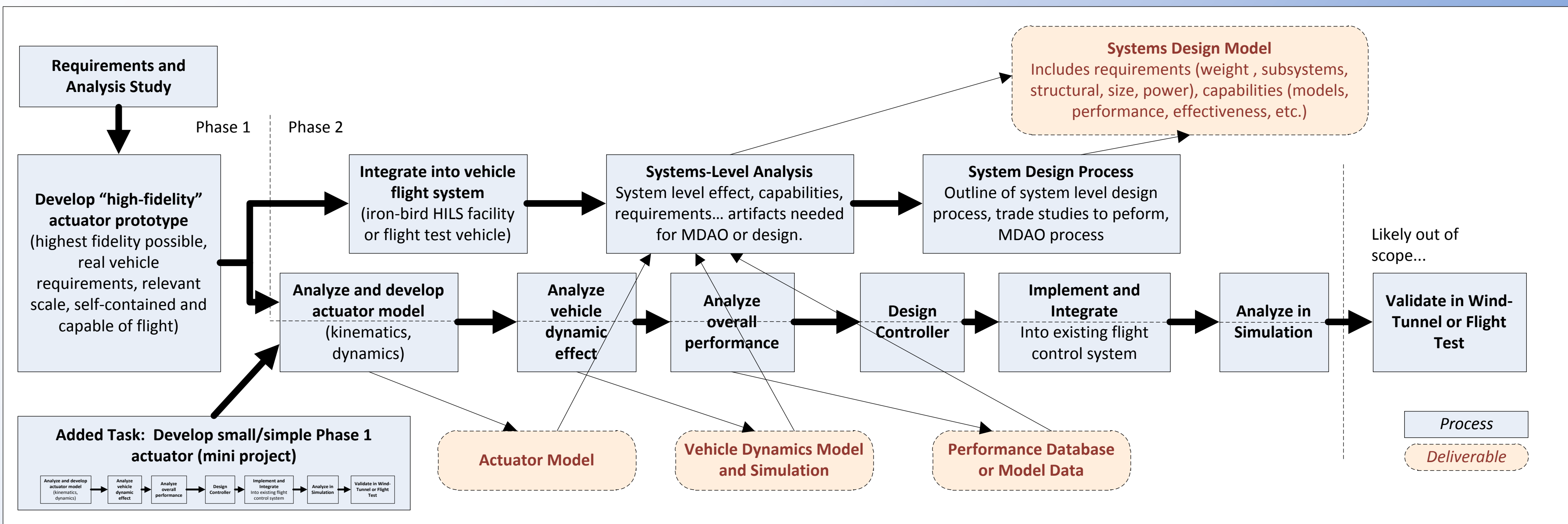

Phase 1 Project Milestone Review

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ID	Modified Phase 1 Task	Status
1.0	PAWS Design and Requ. Study	Complete
2.0	PAWS Prototype Fabrication	On schedule
3.0	Control and Morphing Wing Survey	Complete
4.0	**Perform initial control feasibility / small-scale prototype study**	Complete
	Develop prototype small-scale actuator	
	Integrate into UAV, obtain flight test approval	
	Analyze and model actuator	
	Model and simulate flight dynamics	
	Develop prototype control system	
	Conduct simulation studies	
5.0	PAH/UAS 6DOF M&S	Complete
	Develop mathematical modeling framework	
	Integrate into NASA UAS/PAWS	
6.0	DMoWC Baseline and Sim Integration	Complete
7.0	DMoWC Development and Testing	On schedule
8.0	Final Reporting, Phase 2 Planning	On schedule

PAWS Prototyping
(1.0 and 2.0, Led by KU Team)

DMoWCs Prototyping
(3.0 to 7.0, Led by NASA Team)

Tasks in green were added.

TECHNICAL DETAILS AND ACCOMPLISHMENTS

PART I – PAWS DEVELOPMENT

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AE/University of Kansas

Phase 1 Highlights: PAWS Prototype Development

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- Summary: PAWS Prototype Development
  - Completed initial selection, requirements, airfoil study for the PAWS prototype
  - Selected morphing target for prototype
    - Identified high-lift takeoff and landing shape
    - High-lift airfoil shape provides 50% improvement of C_L-max
  - Completed fabrication of the outer structure of the PAWS
  - On track to deliver PAWS actuator to NASA Ames at the end of FY12, despite project start date delay due to funding issues
  - Successful Phase 1 delivery of prototype allows Phase 2 analysis
  - Phase 2 analysis will provide data for incorporation into design process/MDAO

Target Vehicle Selection: NASA Swift UAS

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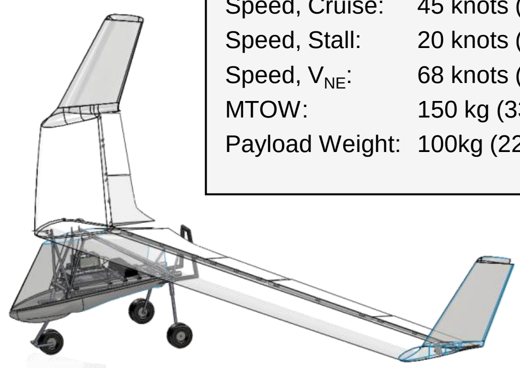
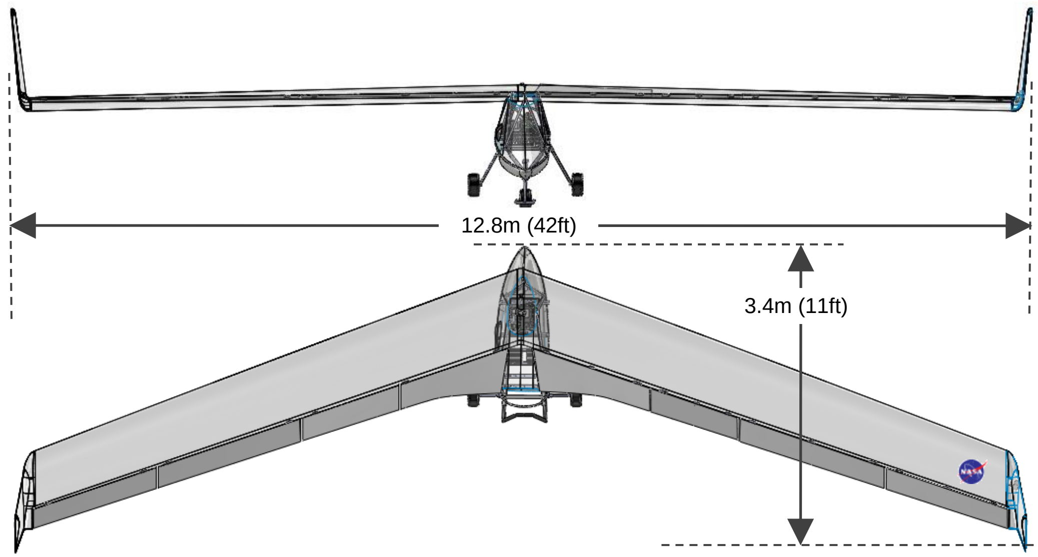
NASA Swift UAS Specifications

Wing Span:	12.8m (42ft)
Length:	3.4m (~11ft)
Wing area:	12.5 m^2 (136 ft^2)
Aspect ratio:	12.9
Speed, Cruise:	45 knots (23 m/s)
Speed, Stall:	20 knots (10 m/s)
Speed, V_{NE}:	68 knots (35 m/s)
MTOW:	150 kg (330 lbs)
Payload Weight:	100kg (220lbs)

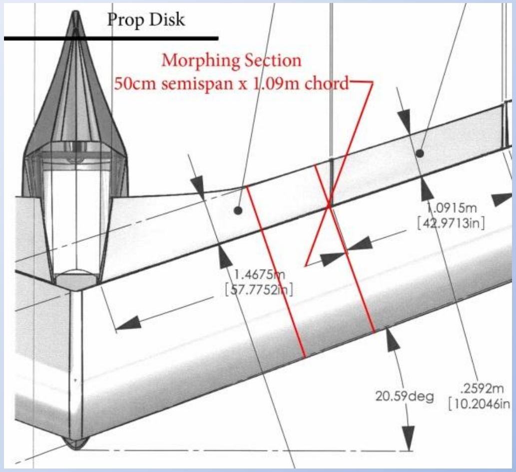


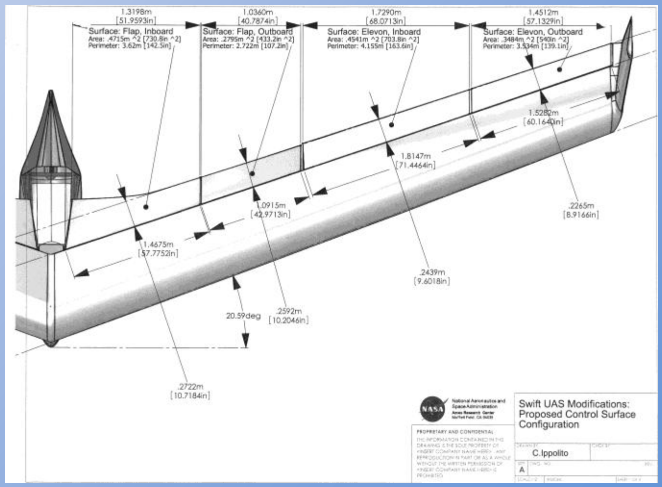


- Needed a vehicle to derive integration and performance requirements, needed a vehicle with existing models and simulations for analysis, needed a vehicle at a manned-aircraft scale
- Swift UAS is a converted high-performance glider capable of carrying two-man payload
- Unique UAS size and payload capacity for low cost
  - Weight limited due to NASA UAS Risk Cat. 2 (medium-size)
  - Designed to safely test experimental controls, full system redundancy
- Flying-wing configuration exhibits similar challenges faced by proposed future aircraft design concepts
- Significant amounts of data available, directly accessible by PI

Phase 1 Highlights: PAWS Prototype Development

- Initial design and requirements study
  - Find ‘morphing target’ as shape requirement for KU prototype
  - PAWS prototype to be fitted to a Swift UAS wing section





Phase 1 Highlights: PAWS Prototype Development

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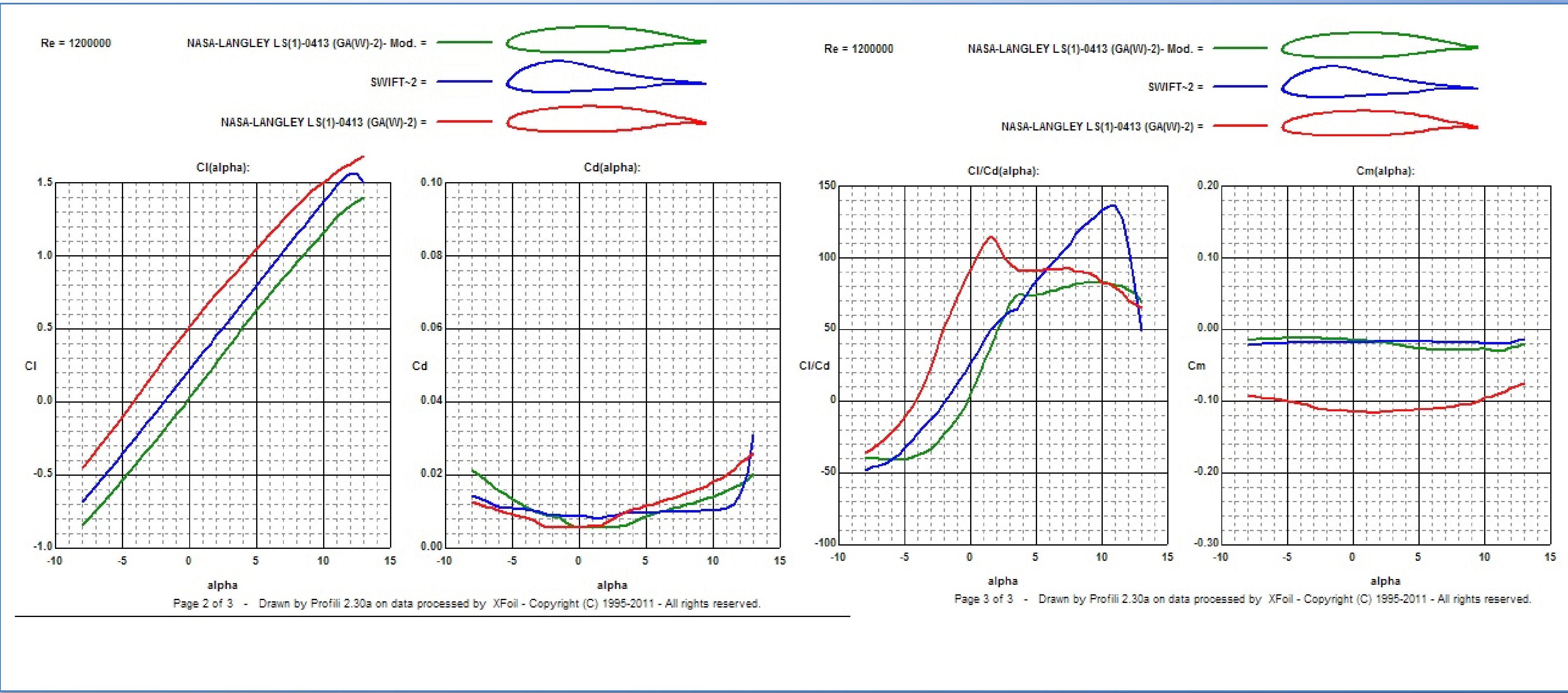
– Comparison with NASA Langley LS(1)-0413, modified LS(1)-0413 appropriate for flying-wing



Phase 1 Highlights: PAWS Prototype Development

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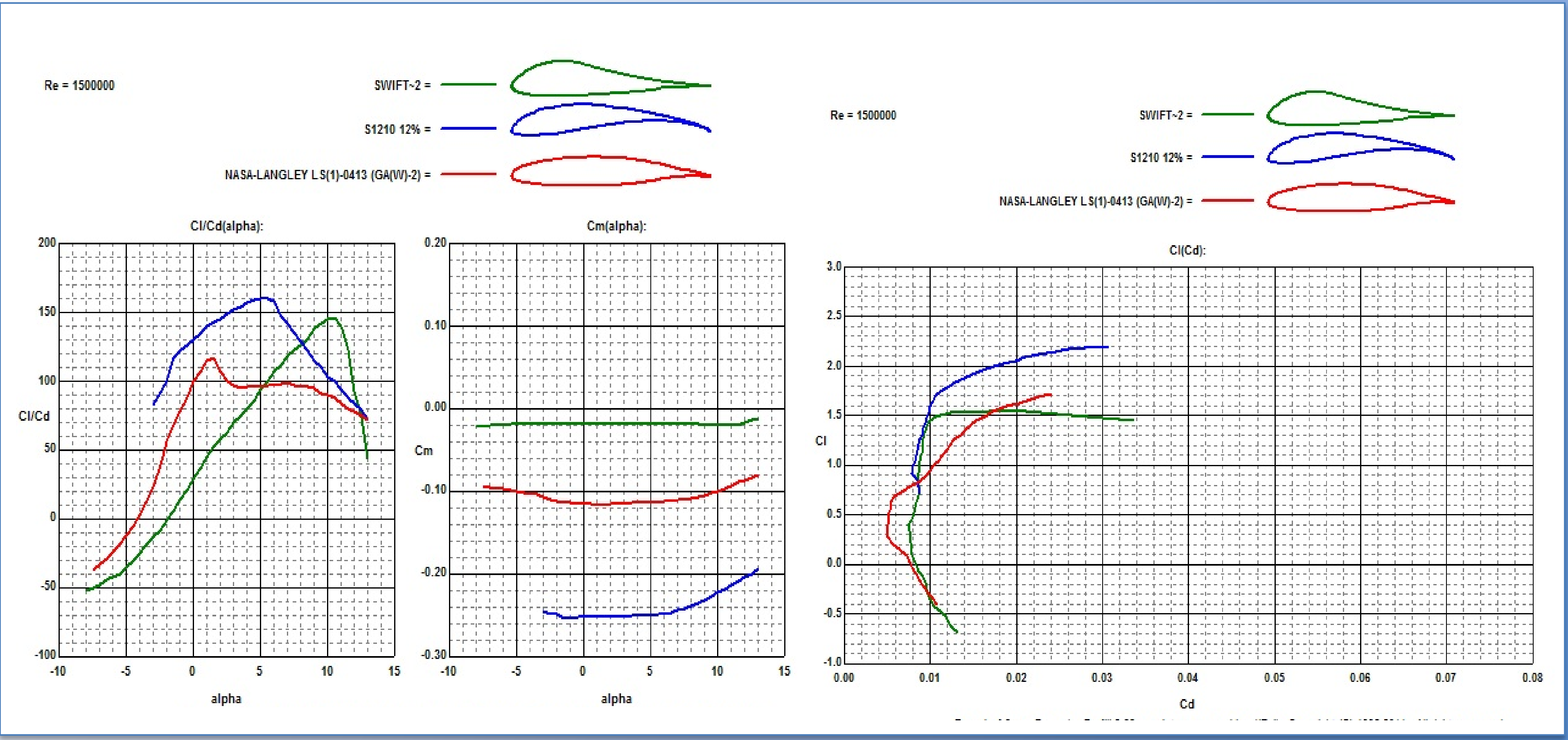
– Comparison with Selig 1210



Phase 1 Highlights: PAWS Prototype Development

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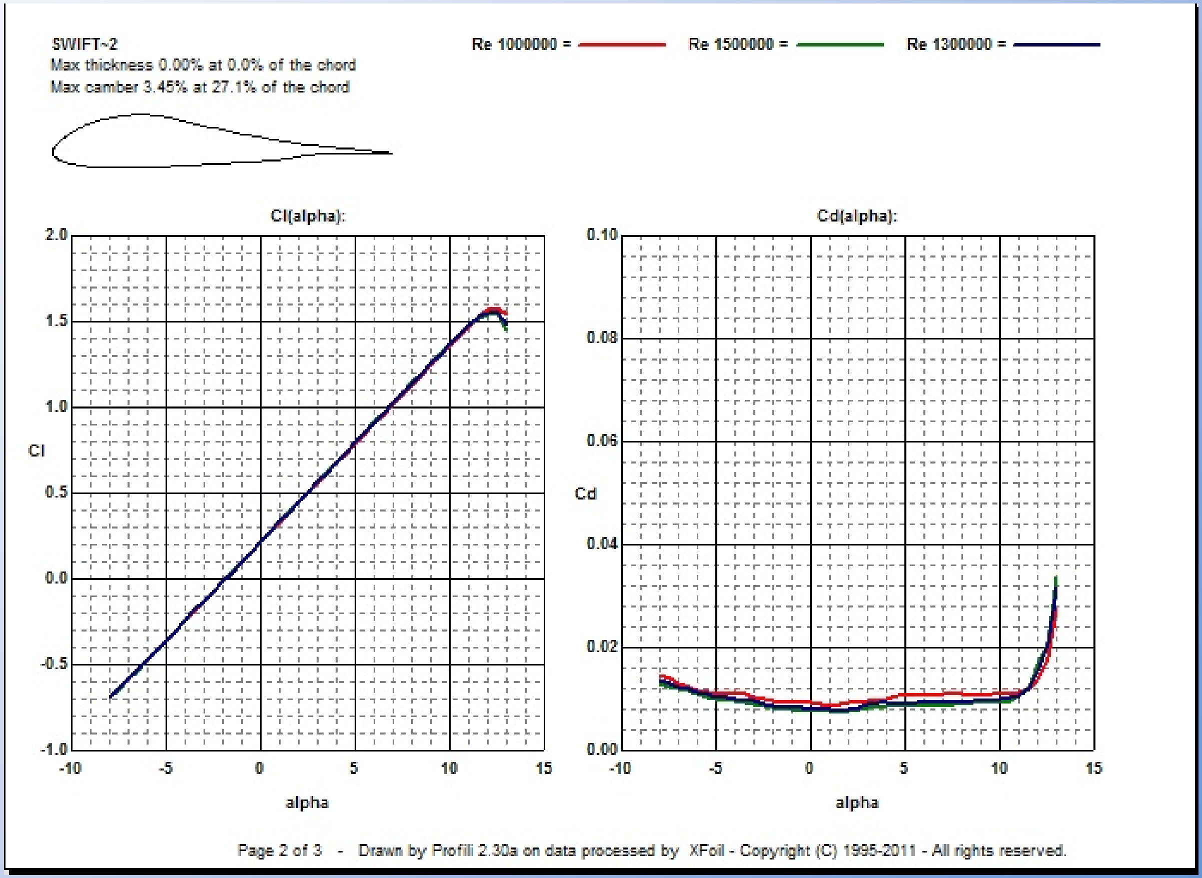
– Swift airfoil performance sweep with rspct to Rn



Phase 1 Highlights: PAWS Prototype Development

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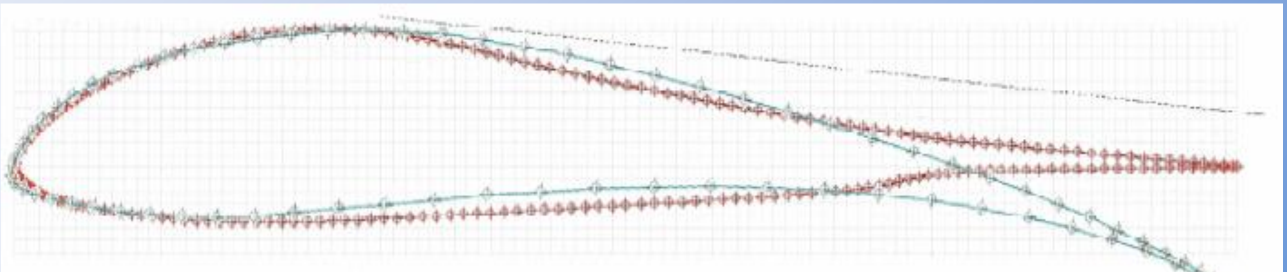
- Swift to Selig 1212 selected as morphing target endpoints
- Prototype requirement
  - Morph between the Swift airfoil in cruise to the Selig 1212 during takeoff and landing
  - Cruise section L/D in cruise will top 140
  - Takeoff/landing Clmax values will approach 2.2 (nearly 50% improvement)
- Comparison of Swift Airfoil with Selig 1212 geometry
  - Leading edge geometric similarities, trailing edge and camber deflection
  - Allows wing torque box to be unmodified



Swift Airfoil vs Selig 1212 geometry

Phase 1 Highlights: PAWS Prototype Development

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What is $C_{L\text{-}max}$ implications for lightweight high-aspect ratio wings?

Estimated implications for LSA* based on a 20% increase of clean C_{Lmax}:**

- 17% reduction in wing wetted area
- 20% increase in aspect ratio
- 10% increase in L/D
- 8% reduction fuel burn and DOC at constant range
- 1.5% decrement in TOW and purchase price at constant range

* 45kts flaps-up stall requirement

** Based on: Roskam "Airplane Design," part I, II, V, and VIII, and Cessna 162 Skykatcher Data

Phase 1 Highlights: PAWS Prototype Development

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- Constructed wing test section
- Below: prototype prior to fitting with adaptive honeycomb cells

Figure 10 110cm Chord x 50cm Semispan Morphing Wing Section Prototype

Unmorphed Swift Airfoil to morphed Selig 1212 Airfoil
(1.1m Chord x 50cm Semispan Airfoil Section)

Phase 1 Highlights: PAWS Prototype Development

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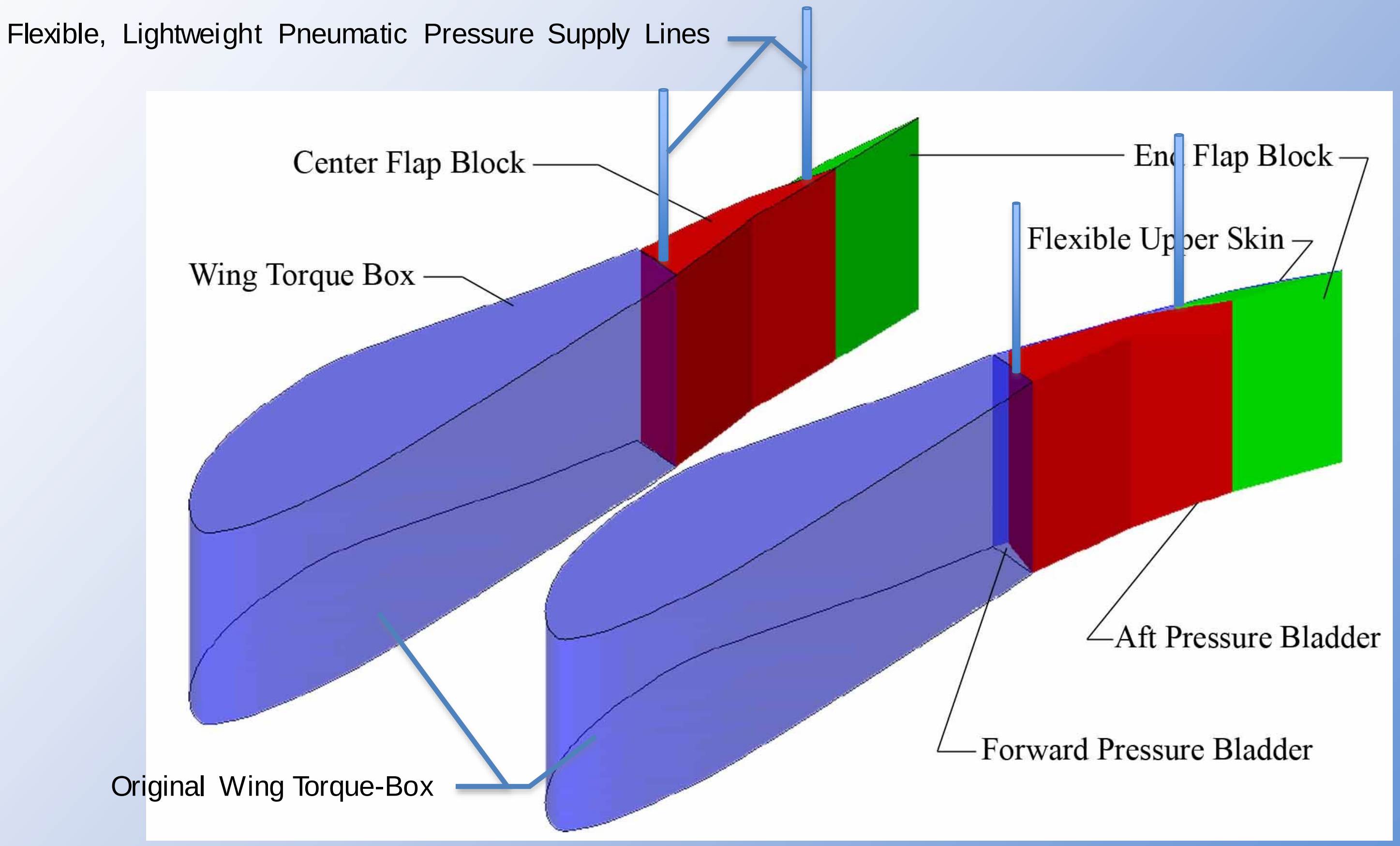
- Prototype design schematic for Swift to Selig 1212 morphing



Phase 1 Highlights: PAWS Prototype Development

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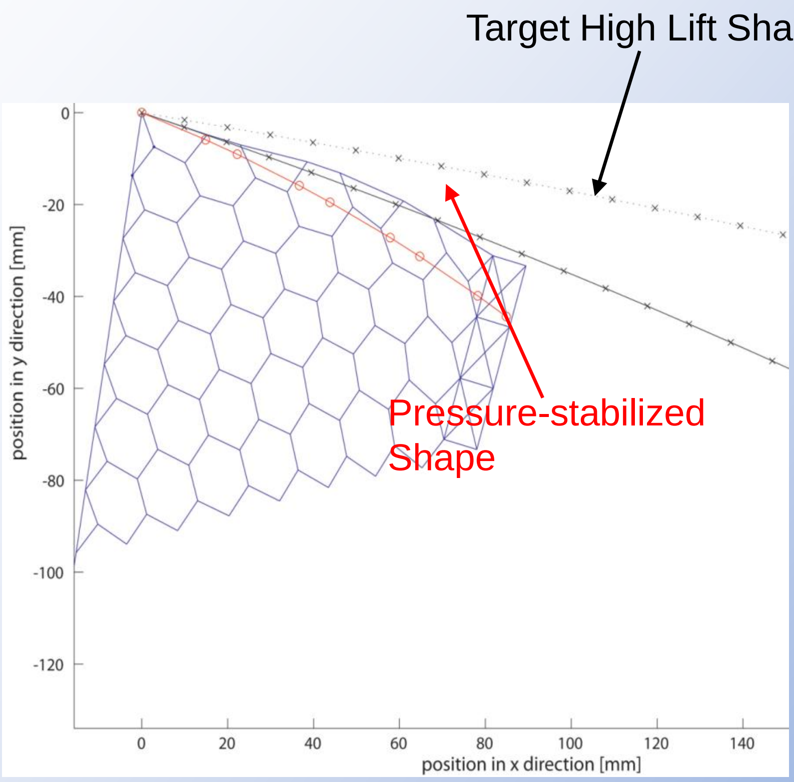
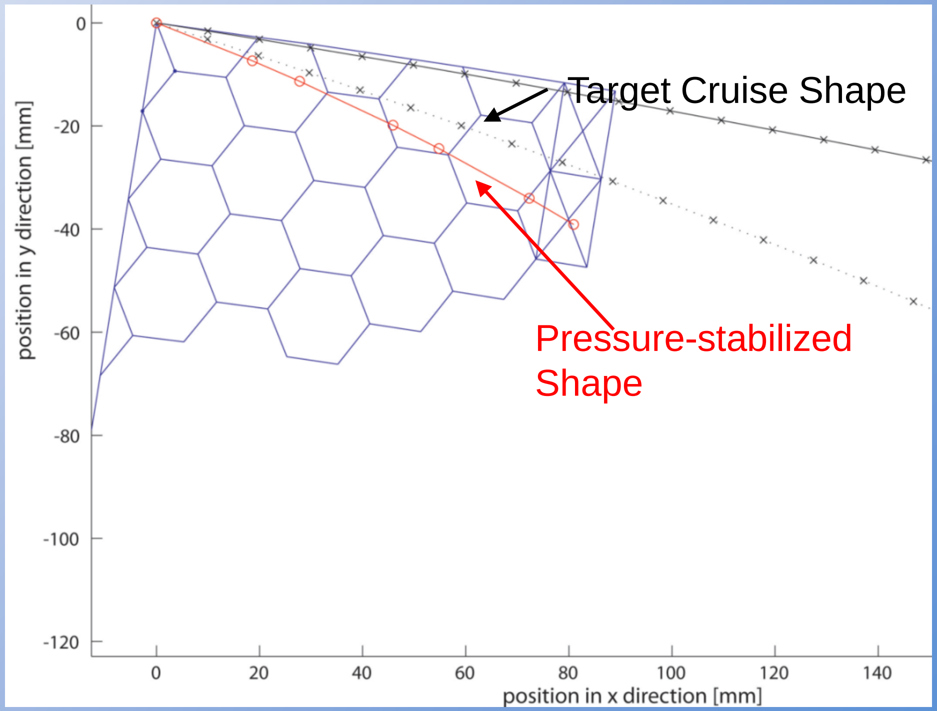
- PAHS modeling for shape control





Theoretical Characterization

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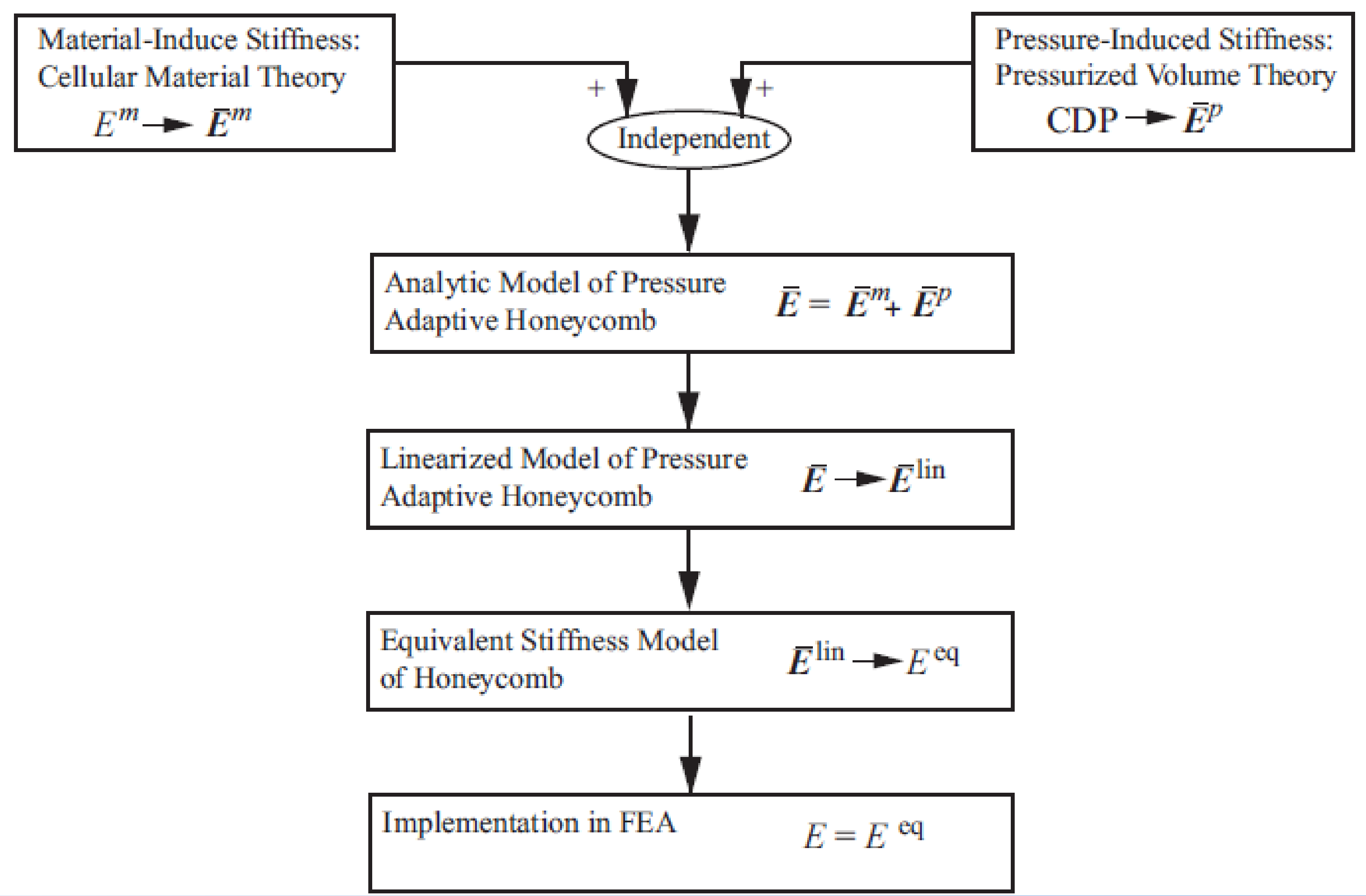

Linear-Elastic Honeycomb

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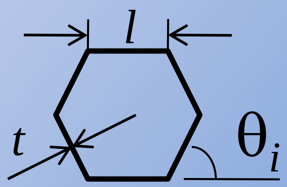
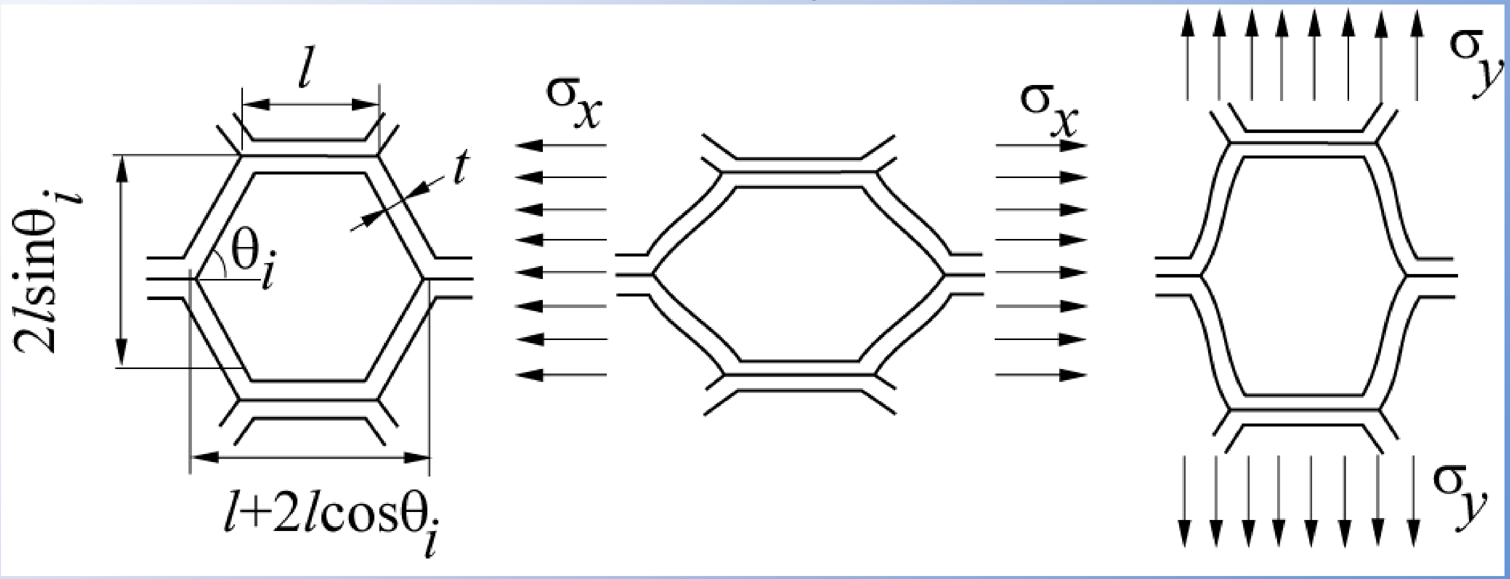
Cellular Material Theory (CMT) after Gibson *et al.* 1988

Considerations:

- Only valid for small thickness-to-length ratio
- Only valid for +/- 20% of strain
- Linear stress-strain relationship





Theoretical Characterization

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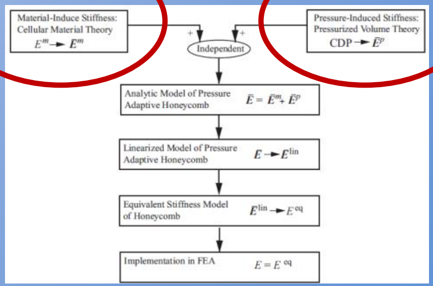
Linear model for honeycomb stiffness moduli:

$$\bar{E}_x^m = E^m \left(\frac{t}{l}\right)^3 \frac{\cos\theta_i + 1}{\sin^3\theta_i} \quad \text{and} \quad \bar{E}_y^m = E^m \left(\frac{t}{l}\right)^3 \frac{\sin\theta_i}{(1+\cos\theta_i)\cos^2\theta_i}$$

To find pressure-induced stiffness moduli:

$$W_{use} = \int_{V_i}^{V} p\mathrm{d}V - p_a(V - V_i) \quad \text{and} \quad W_{ex} = \int_s F\mathrm{d}s$$

Assumptions:
- Rigid members connected by hinges
- Constant pouch-to-hexagon volume ratio
- No friction forces between pouch and wall



Theoretical Characterization

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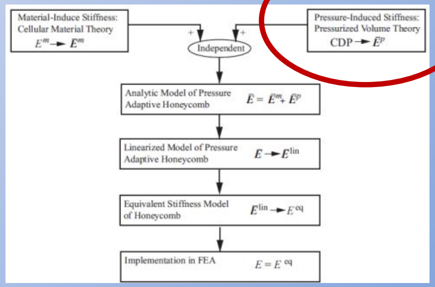

<u>Global stress-strain relations:</u>

@ constant pressure:

$$\sigma_x = \frac{1}{l^2(1+\cos\theta_i)} \times \frac{(p-p_a)(V-V_i)}{\sin\theta - \sin\theta_i} \quad \text{and} \quad \sigma_y = \frac{1}{l^2\sin\theta_i} \times \frac{(p-p_a)(V-V_i)}{\cos\theta - \cos\theta_i}$$

@ constant mass:

$$\sigma_x = \frac{1}{l^2(1+\cos\theta_i)} \times \frac{mRT\ln(V/V_i) - p_a(V-V_i)}{\sin\theta - \sin\theta_i} \quad \text{and} \quad \sigma_y = \frac{1}{l^2\sin\theta_i} \times \frac{mRT\ln(V/V_i) - p_a(V-V_i)}{\cos\theta - \cos\theta_i}$$

with

$$V = \zeta l^2(1+\cos\theta)\sin\theta$$

Four-Cell Tensile Test of Steel Honeycombs (cont.)

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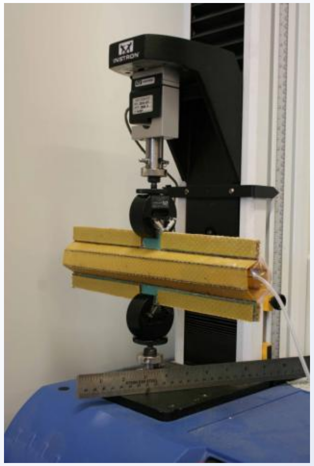

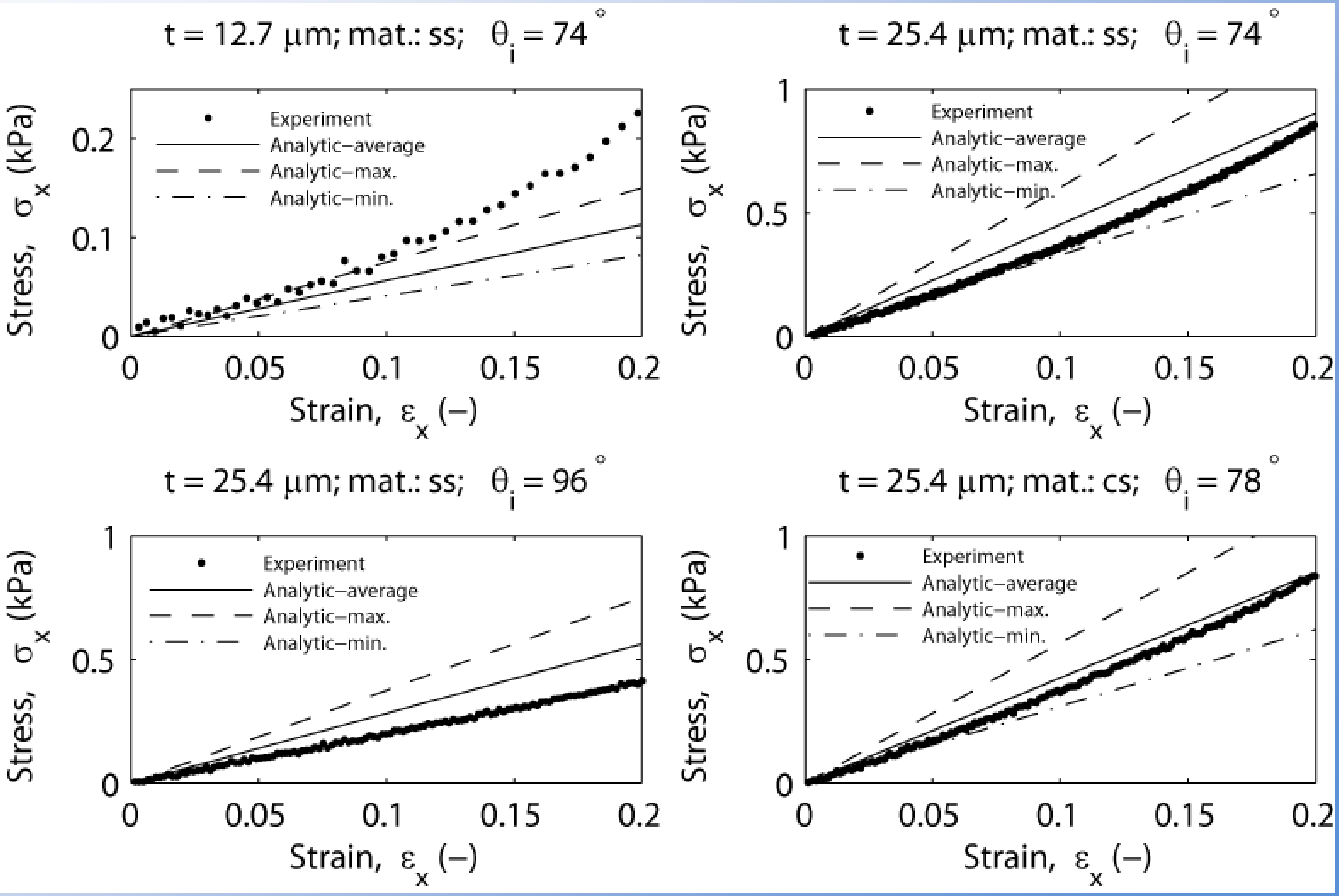

Multi-Cell Compression Test (cont.)

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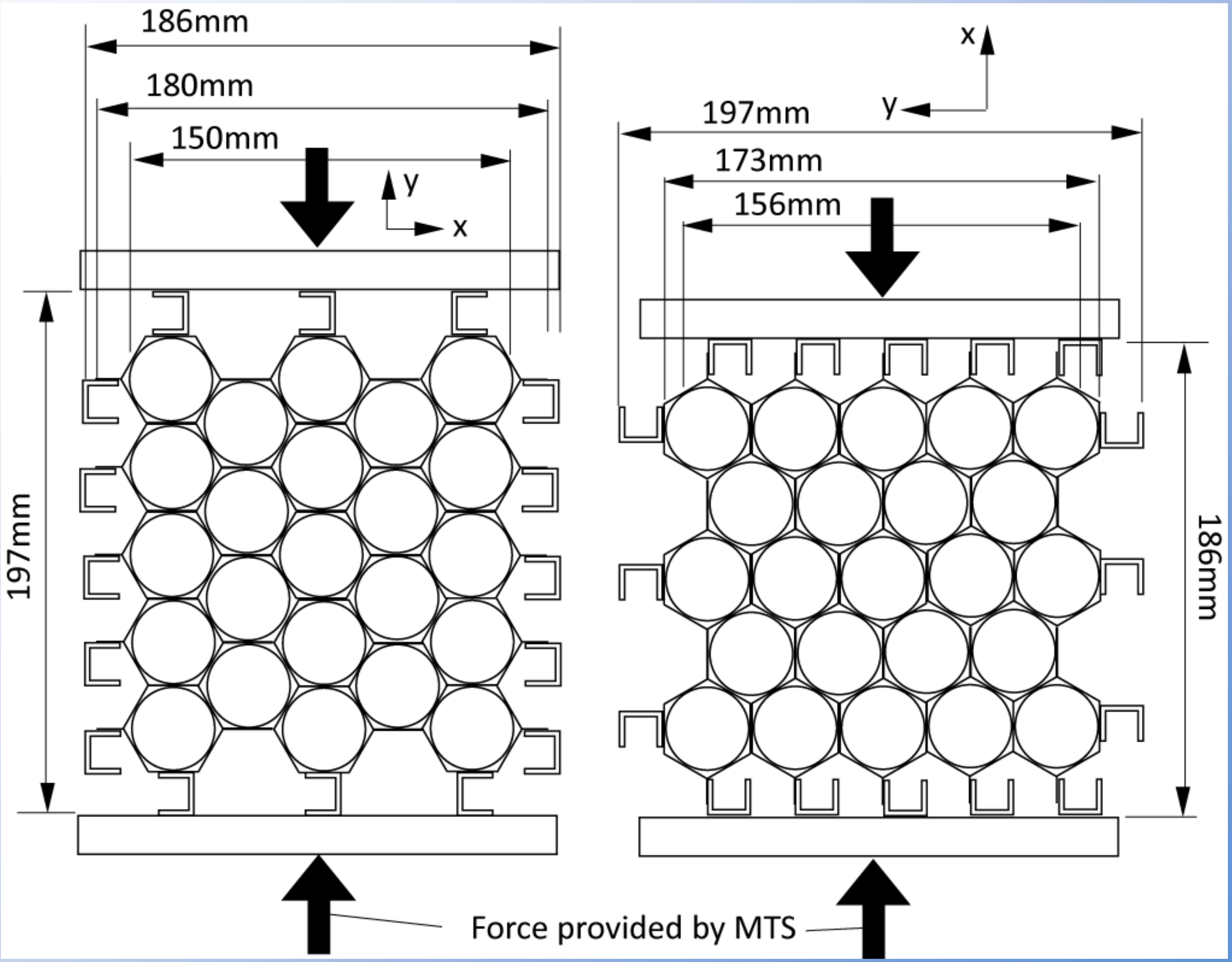

Phase 1 Highlights: PAWS Prototype Development

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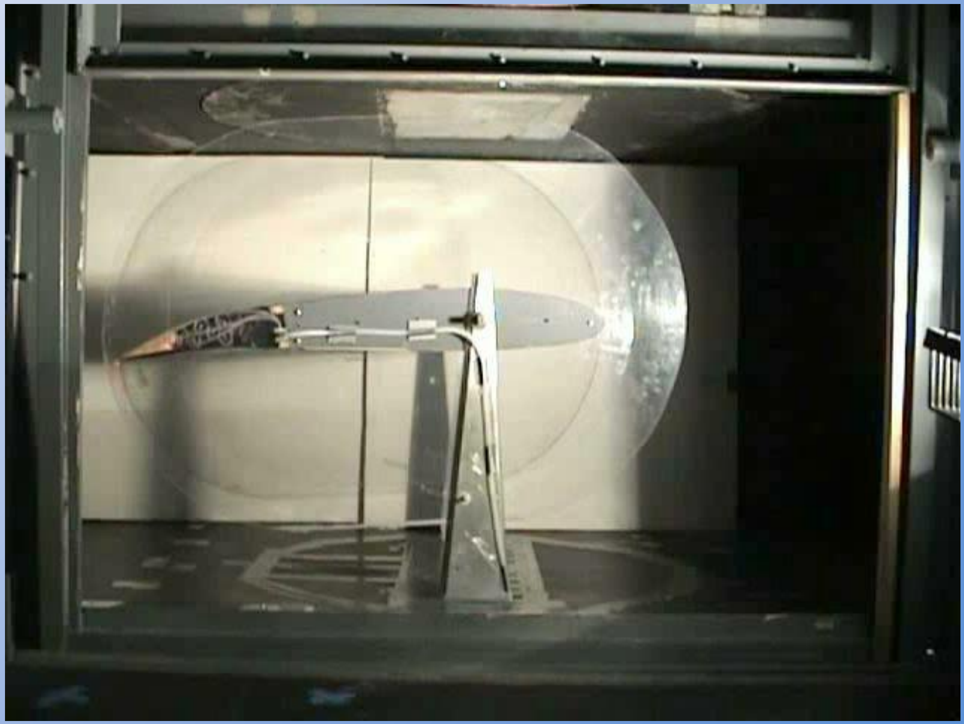
- Installation is currently underway on schedule for completion at the end of Phase 1



TECHNICAL DETAILS AND ACCOMPLISHMENTS

PART II – DMOWCS DEVELOPMENT

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Phase 1 Highlights

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- Modeling and Simulation
  - Completed derivation of a parallelized mathematical model of the morphing wing vehicle utilizing a vortex-lattice solver that integrates into the vehicle's flight dynamics model.
  - Completing creation of a simulation environment that can be integrated into NASA's hardware in the loop simulation facility.
  - Conducted a study to investigate parallelization of the simulation model to increase run-time performance.
  - Parallelized and ported model to a many-core environment (NVIDIA CUDA GPU)

Traditional Simulation and Control Architecture

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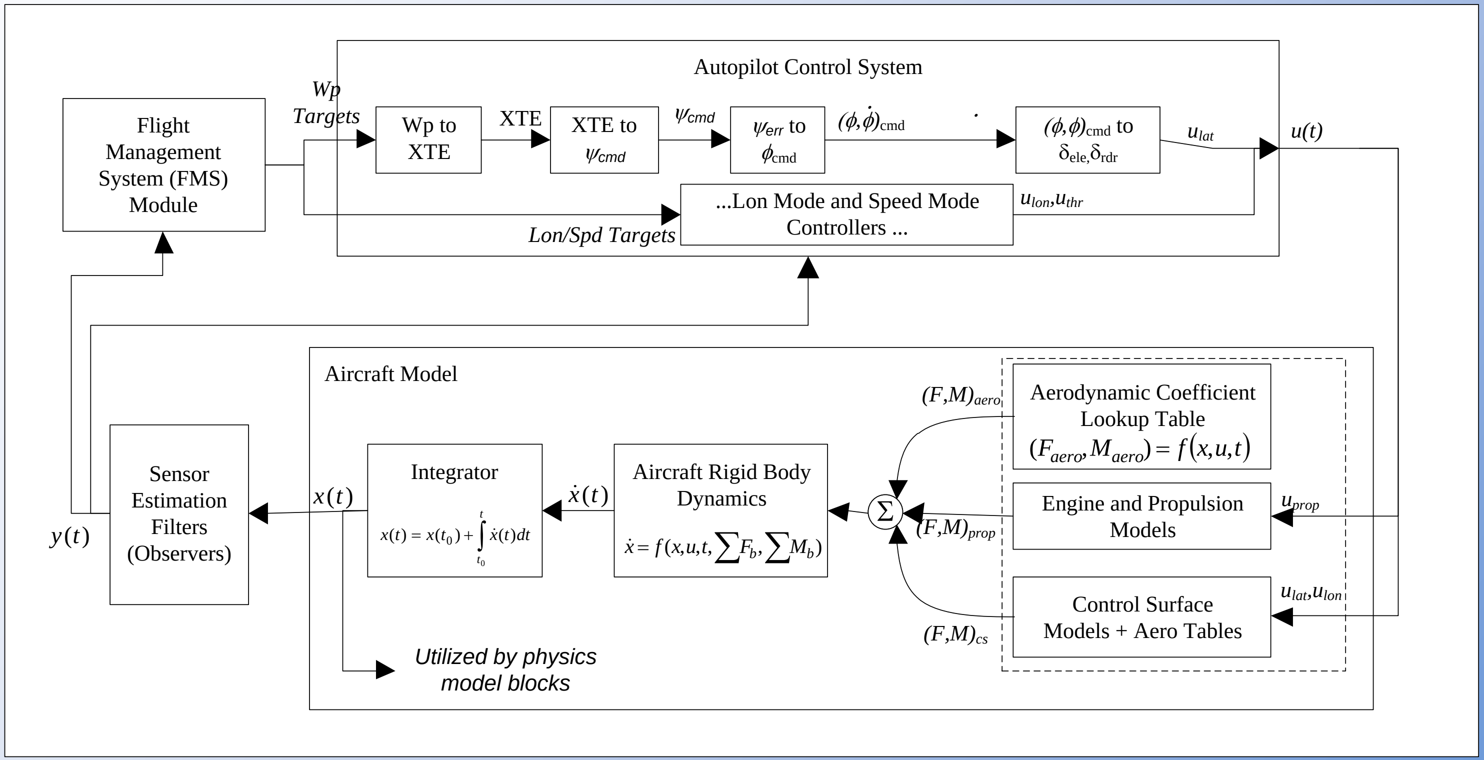

Two Part Parallelized Model

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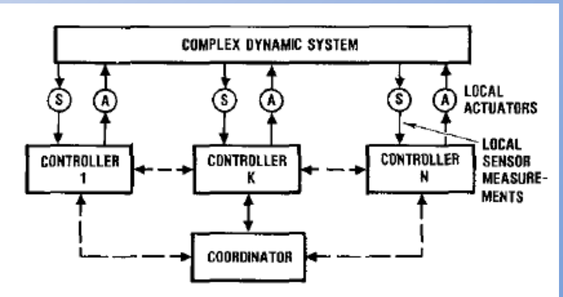
- Two components: topological model + physics-based element model
- Topological Model
  - Graph-based model to describe phenomena physics and control system topology
  - Variable granularity definition with variability in structure



- Physics-Based Model (per vertex/edge)
  - Inviscid 2D airfoil analysis using steady-state vortex-panel method to compute Cp distribution and C_L per unit section
  - Induced drag from finite wing theory using trailing edge vortices
  - Viscous skin friction drag needs to be determined (currently researching)
  - Separation drag will be ignored, but can be predicted
  - Steady solution (non-steady vortex-panel additions will be invested in phase 2)
  - Applicable to multiple vehicles and control problems

Parallelized Architecture for Decentralized Flight Modeling and Control

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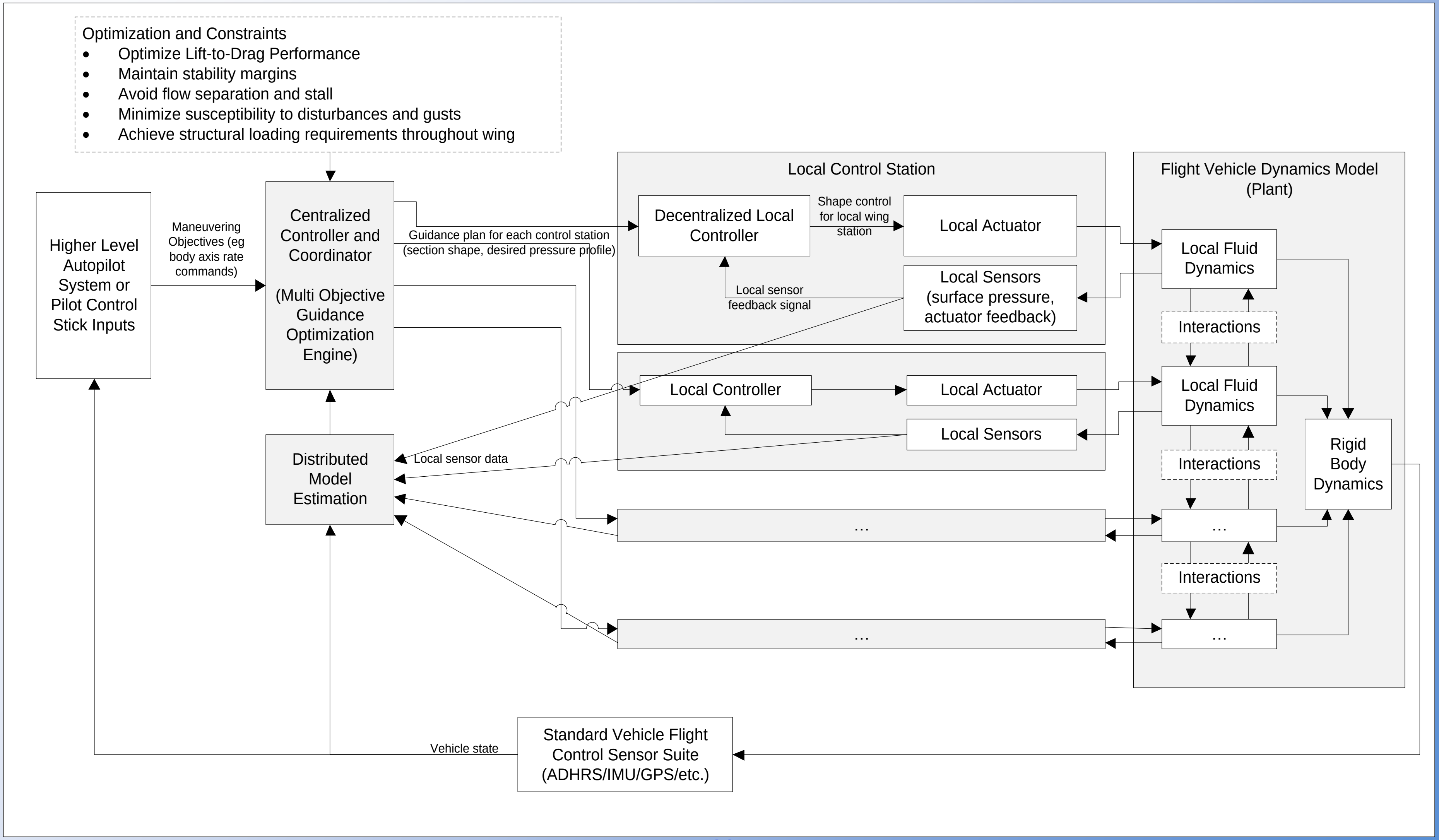
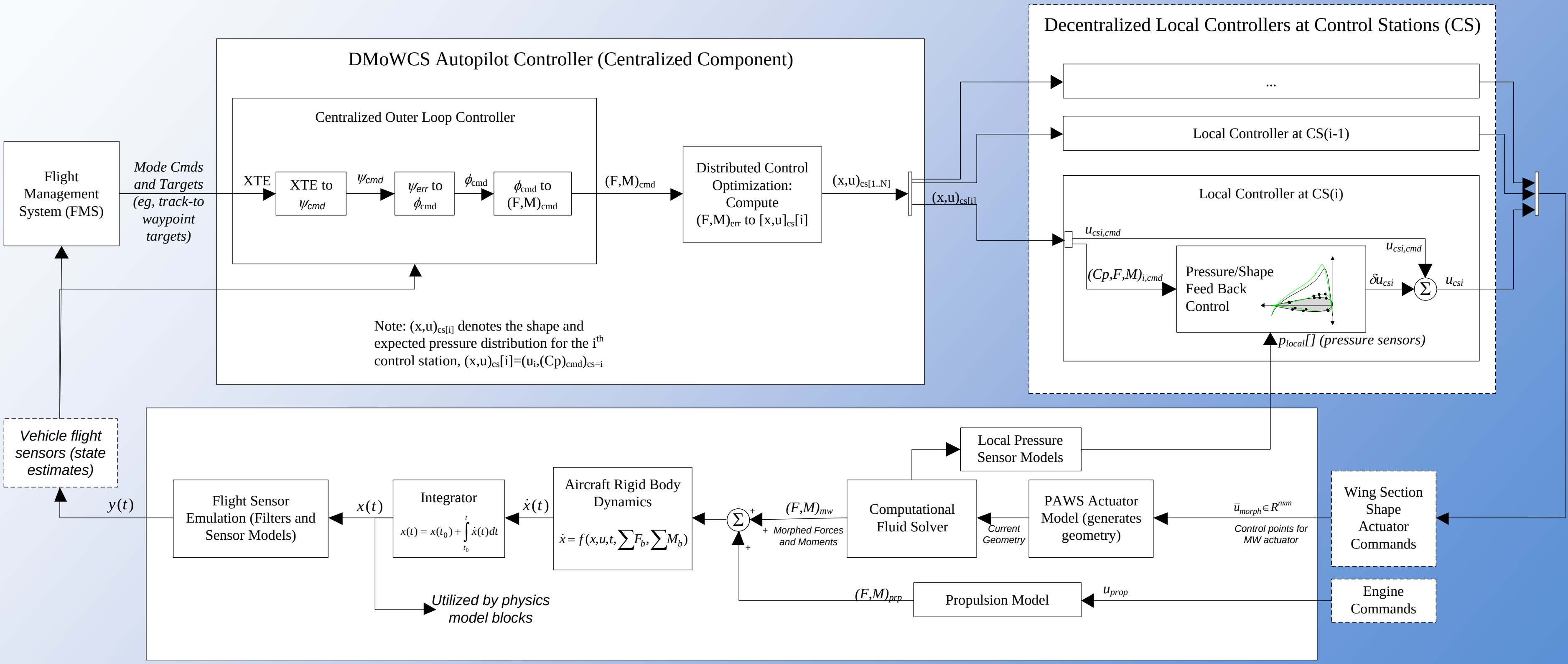


Parallelized Architecture for Decentralized Flight Modeling and Control

Simulation Environment



Control Architecture – Morphing Wing Concept Example

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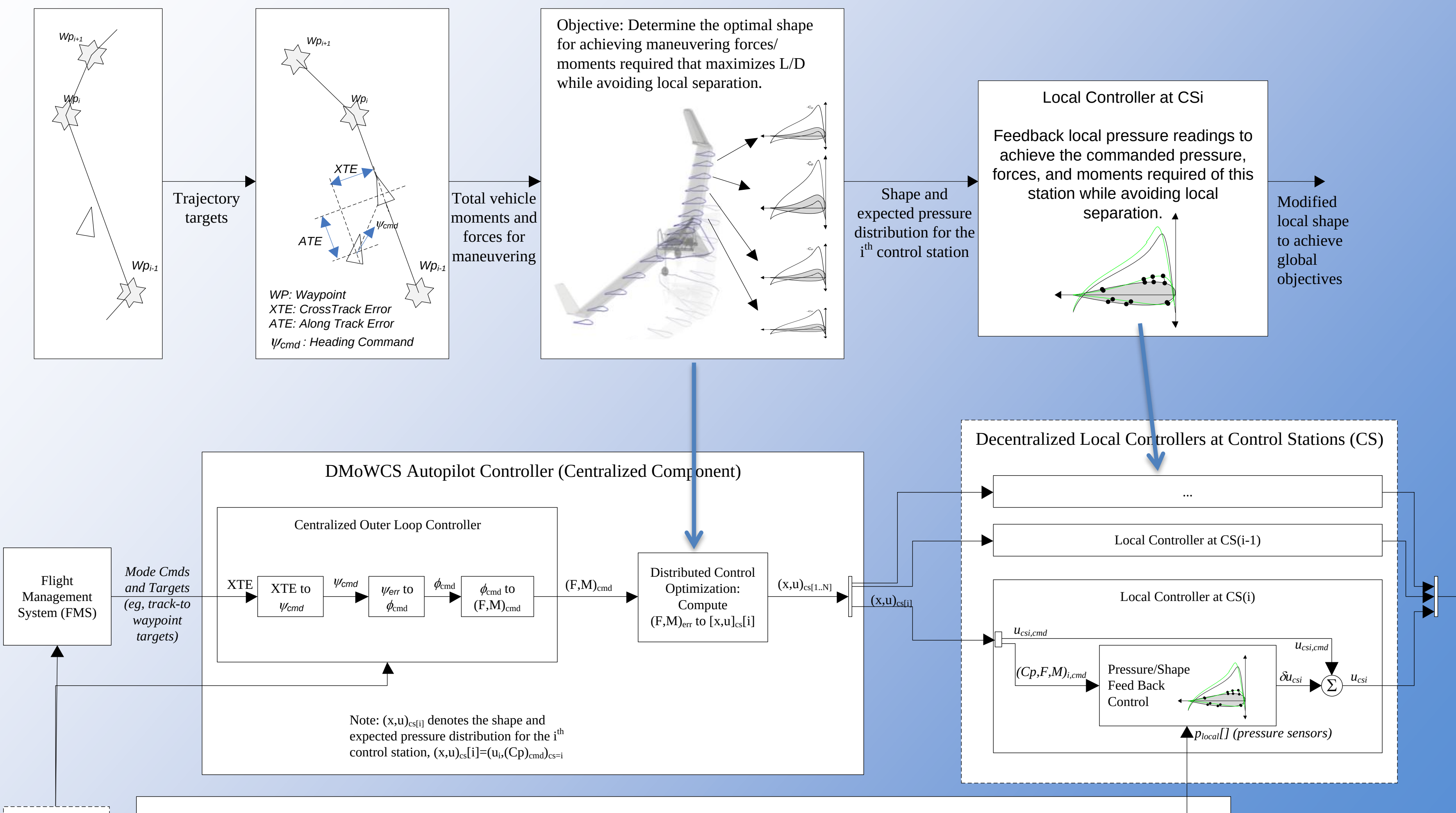

Graph-Based Topological Model

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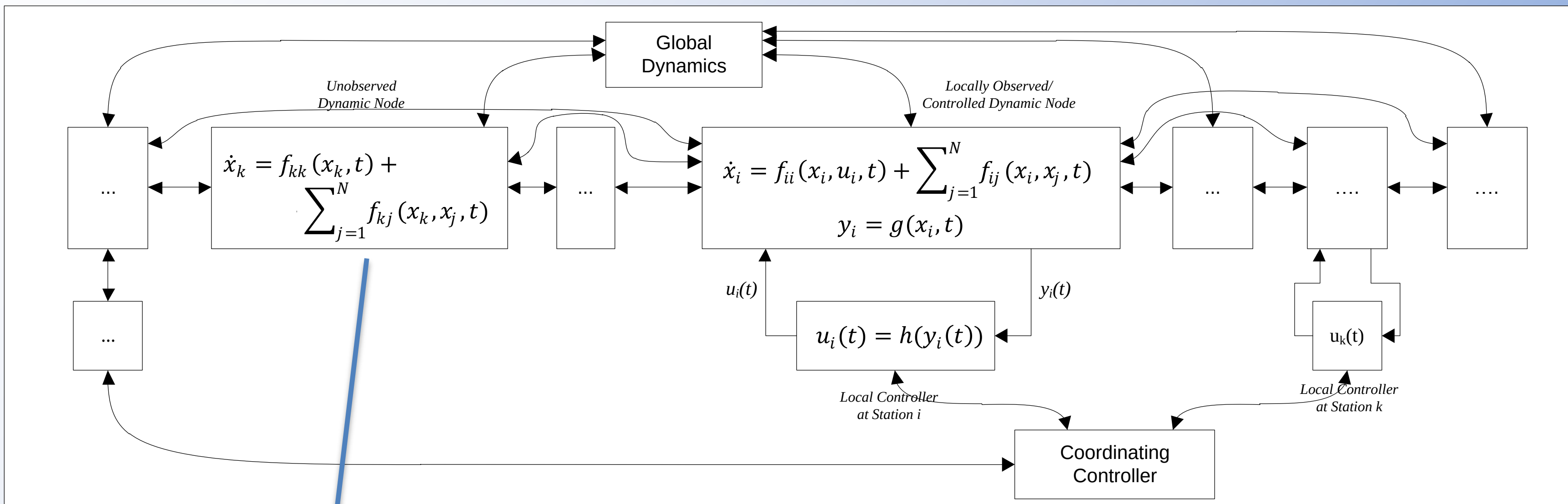

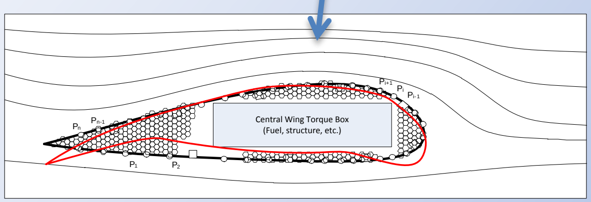

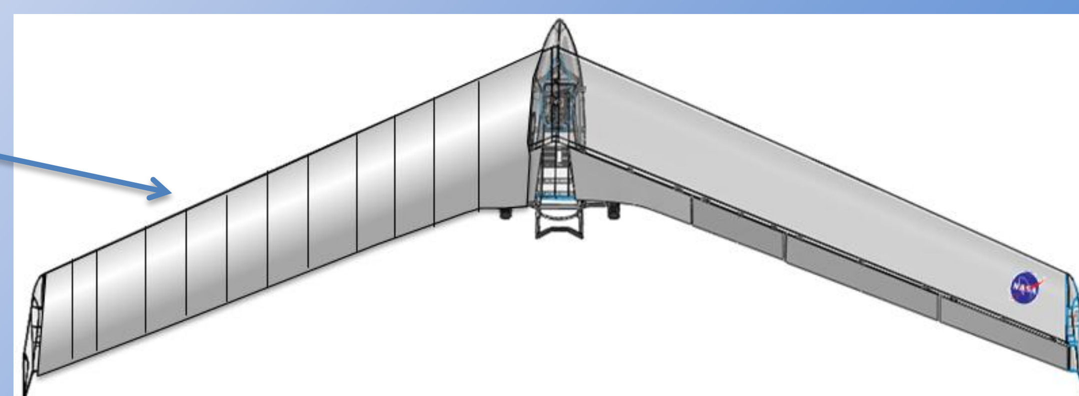

Physics-Based Element Model

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Global Integration - 6-DOF Equations of Motion

$$\frac{d}{dt}\mathbf{P}_e = (\tilde{\boldsymbol{\Omega}}_{Earth_e}\mathbf{P}_e) + \mathbf{R}_{b2e}\mathbf{V}_b$$

$$\frac{d}{dt}\mathbf{V}_b = -(\boldsymbol{\omega}_b \times \mathbf{v}_b) - \left(\mathbf{R}_{e2b}\boldsymbol{\Omega}^2_{Earth_e} + \mathbf{R}_{e2b}\boldsymbol{\Omega}_{Earth_e}\mathbf{R}_{b2e}\boldsymbol{\omega}_b\right) + \mathbf{R}_{e2b}\mathbf{g}_e + \frac{1}{m}\mathbf{F}_B$$

$$\frac{d}{dt}\mathbf{q} = -\frac{1}{2}\tilde{\mathbf{q}}\mathbf{q}$$

$$\frac{d}{dt}\boldsymbol{\omega}_b = -\mathbf{J}^{-1}\tilde{\boldsymbol{\omega}}_b\mathbf{J} + \mathbf{J}^{-1}\mathbf{T}_b$$

$$\mathbf{F}_b = \mathbf{F}_{aero\ b} + \mathbf{F}_{prop\ b} + \mathbf{F}_{morph\ b}$$

$$\mathbf{T}_b = \mathbf{T}_{aero\ b} + \mathbf{T}_{prop\ b} + \mathbf{T}_{morph\ b}$$

Assumption

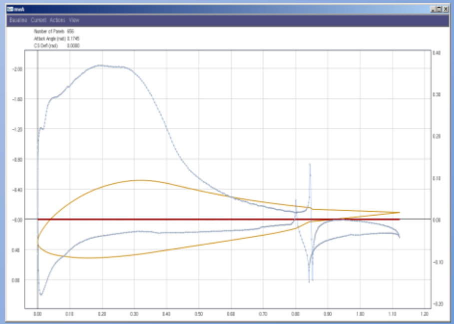
$$\mathbf{F}_b \approx \mathbf{F}_{areo\ b} + \mathbf{M}_{ac2b}(\mathbf{F}_{mw} - \mathbf{F}_{umw})$$

$$\mathbf{T}_b \approx \mathbf{T}_{areo\ b} + \mathbf{M}_{ac2b}(\mathbf{T}_{mw} - \mathbf{T}_{umw})$$

Alternative

Aerodynamics forces are computed completely by unsteady Vortex-Panel.

Evaluate F_{mw} and T_{mw} through 2D Vortex-Panel Evaluation



$$\mathbf{F}_{ac} = \sum_{i=1}^{N}\left(P_\infty + \left(1 - \frac{\gamma_i^2}{U_\infty^2}\right)\frac{1}{2}\rho_\infty U_\infty^2\right)\Delta s_i\ \hat{n}_i$$

$$\mathbf{T}_{ac} = \sum_{i=1}^{N}\left((P_i - P_{cg}) \times \mathbf{F}_{i\,ac}\right)$$

$\psi(s)$ Stream Function

$\gamma_i(s)$ Surface Velocities

Find $v = [\bar{\gamma}, \tilde{\psi}]^T$ by evaluating

$$\begin{bmatrix} K_{11} & K_{12} & \dots & K_{1N} & 1 \\ K_{21} & K_{22} & & K_{2N} & 1 \\ \vdots & & \ddots & & \vdots \\ K_{N1} & K_{N2} & \dots & K_{NN} & 1 \\ 1 & 0.. & ..0 & 1 & 0 \end{bmatrix}_{(N+1\times N+1)} \begin{bmatrix} \gamma_1 \\ \gamma_2 \\ \vdots \\ \gamma_N \\ \tilde{\psi} \end{bmatrix}_{(N+1)} = \begin{bmatrix} y_1 U_\infty cos\alpha - x_1 U_\infty sin\alpha \\ y_2 U_\infty cos\alpha - x_2 U_\infty sin\alpha \\ \vdots \\ y_N U_\infty cos\alpha - x_N U_\infty sin\alpha \\ 0 \end{bmatrix}_{(N+1)}$$

Where

$$K_{ij} = \frac{1}{2\pi}\left\{\frac{1}{2}\left[x_{j+1}\ln\left(x_{j+1}^2 + y_{j+1}^2\right) - x_j\ln\left(x_j^2 - y_j^2\right)\right] - \left(x_{j+1} - x_j\right) + y_j\left[\tan^{-1}\left(\frac{y_j}{x_j}\right) - \tan^{-1}\left(\frac{y_{j-1}}{x_{j-1}}\right)\right]\right\} \quad for\ i \neq j$$

$$K_{ii} = \frac{\Delta s_j}{2}\left(\ln\left(\frac{\Delta s_j}{2}\right) - 1\right) \quad for\ i = j$$

Physics-Based Model (per-vertex) – Drag

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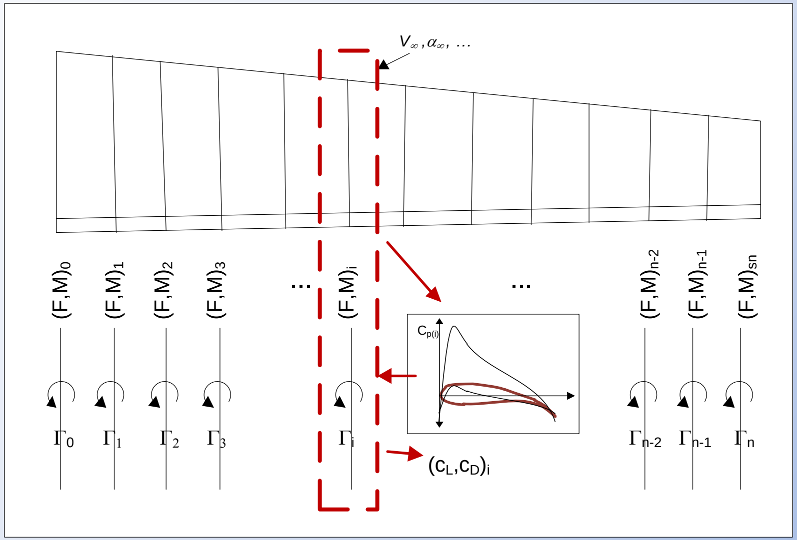
- Capture major components of drag

  Drag : $D = D_{induced} + D_{skin\_fric} + D_{separation} + \ldots$

- Approximate 3D induced effects using trailing vortices



- Fundamental equation of finite-wing theory

$$\alpha_a(y_0) = \left(\frac{2\Gamma}{m_0 V_\infty c}\right) y_0 + \frac{1}{4\pi V_\infty} \int_{-b/2}^{b/2} \frac{(d\Gamma/dy)_{wing}}{y_0 - y} dy$$

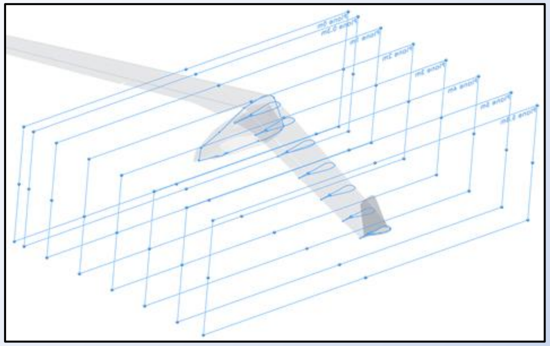
- Fourier series for arbitrary circulation distribution

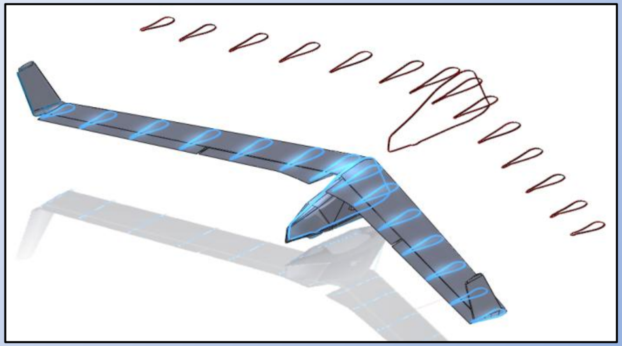
$$\Gamma = \frac{1}{2} m_{0_s} c_s V_\infty \sum_{n=1}^{\infty} A_n \sin(n\theta)$$

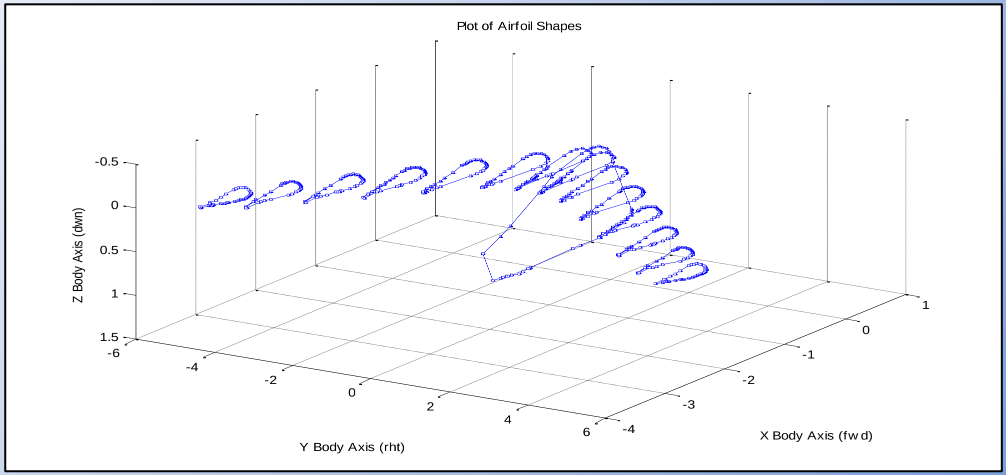
- Numerical approach in (Phillips, 2004)

- Researching incorporate skin friction model

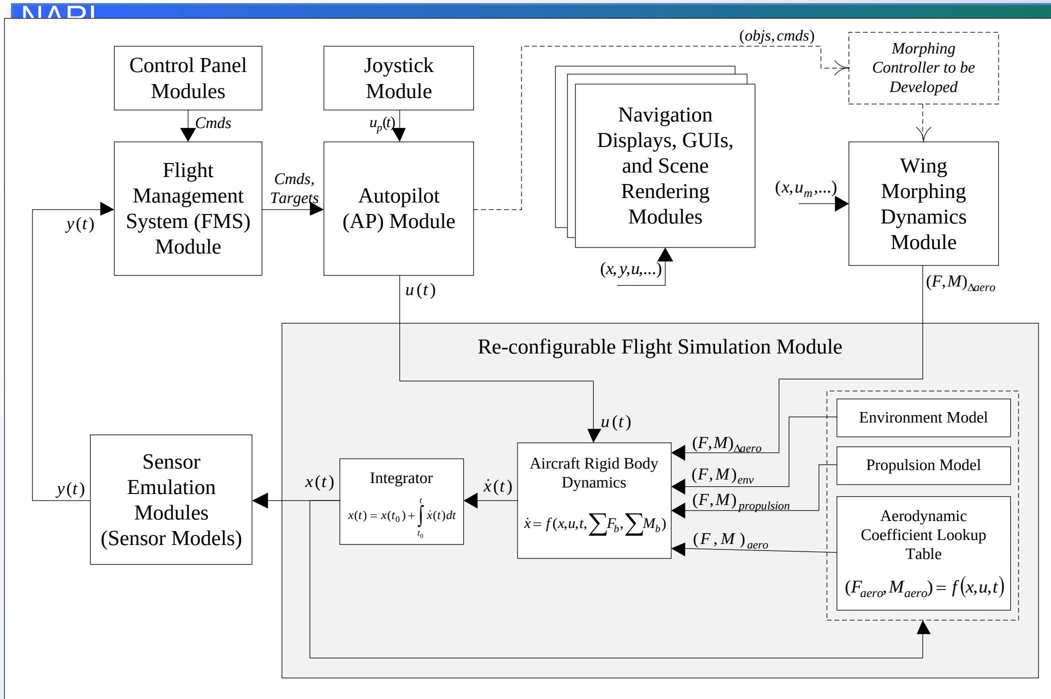
Modeling of the Swift UAS

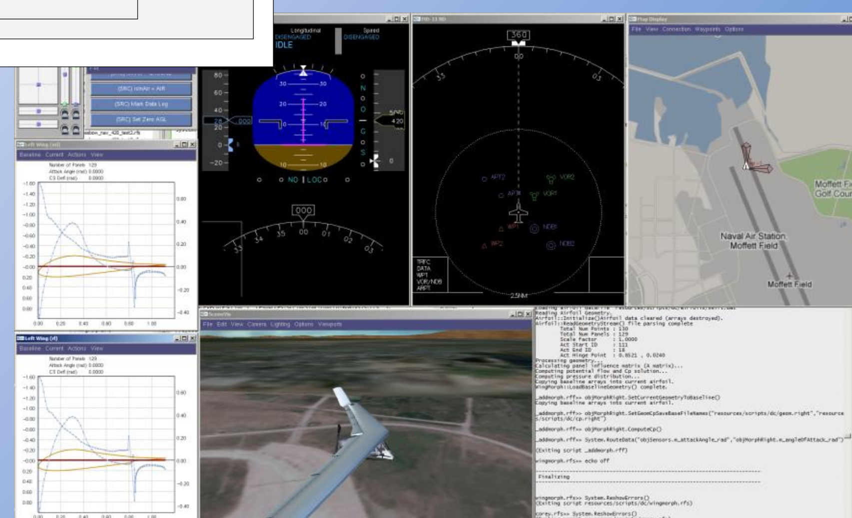






Simulation in Reflection Architecture





Real-Time Physics Processing Pipeline

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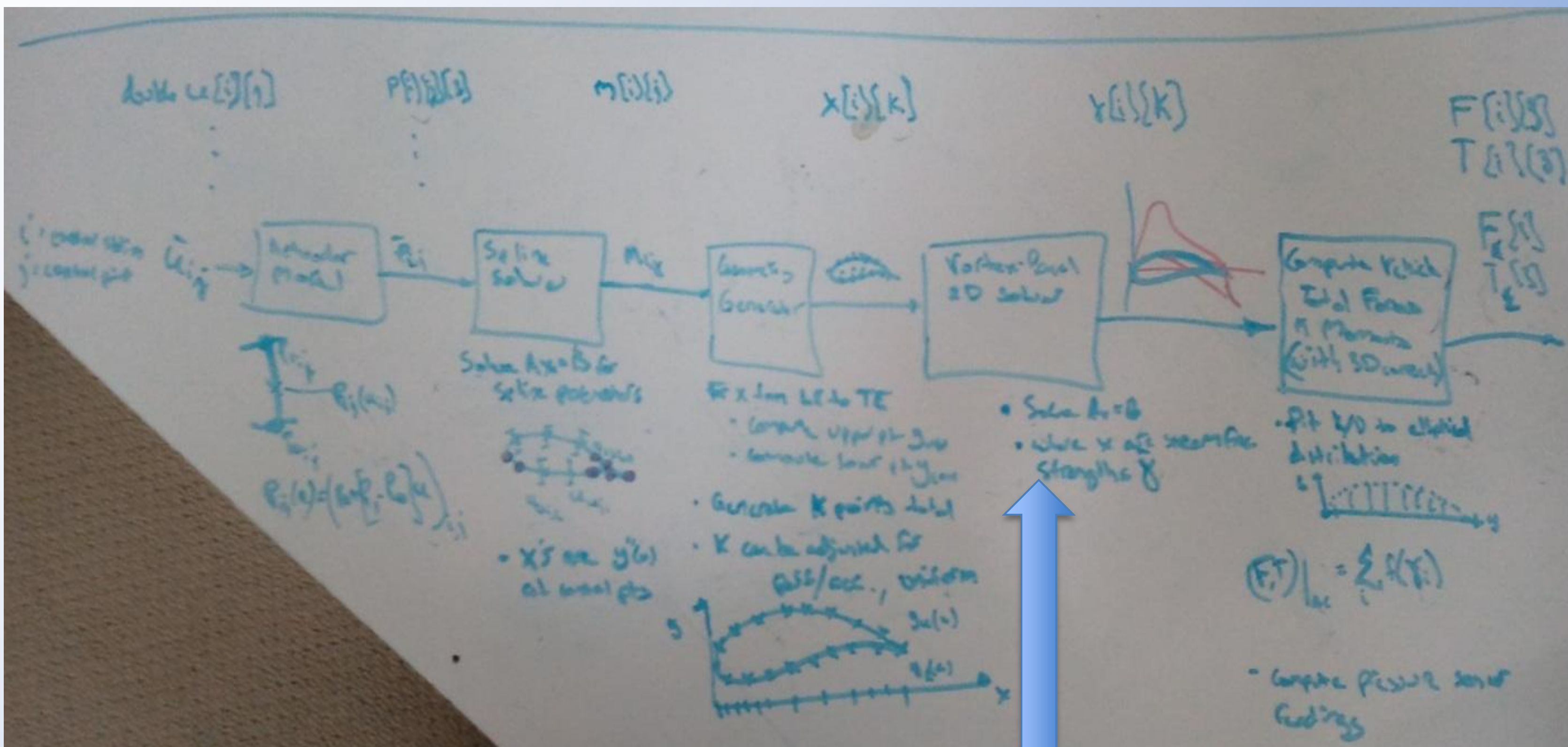

Optimized on GPU

Real-Time Optimization Algorithm

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- Propose new Random Subcomplement Search Tree (RST) Framework
  - Approach inspired by random root-tree and probabilistic roadmaps
  - Requires fast evaluation of model dynamics
  - Research goal: continue to formalize approach, parallelized algorithms for faster implementation with more complex models

RST - Problem Formulation

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Given a system $\mathcal{S}$ where $f: \mathcal{X} \times \mathcal{U} \times \mathcal{T} \rightarrow \mathbb{R}^n$, $h: \mathcal{X} \times \mathcal{T} \rightarrow \mathcal{Y}$, state space $x \in \mathcal{X} \subseteq \mathbb{R}^n$, input space $u \in \mathcal{U} \subseteq \mathbb{R}^m$, output space $y \in \mathcal{Y} \subseteq \mathbb{R}^p$, and time is defined over the convex interval $t \in \mathcal{T} \subseteq \left(0..t_f\right)$.

$$\mathcal{S}: \begin{cases} \dot{x}(t) = f(x(t), u(t), t) \\ y(t) = x(t) \end{cases}$$

Given constraints where $C_{e_i}, C_{i_i}: \mathcal{X} \times \mathbb{R}^n \times \mathcal{U} \times \mathcal{T} \rightarrow \mathbb{R}$

$$C = \{C_e, C_i\}$$
$$C_{e_i}(x, \dot{x}, u, t) = 0$$
$$C_{i_i}(x, \dot{x}, u, t) < 0$$

Given performance objectives J, where $L = \left[L_1..L_{n_L}\right]^T$, where $\phi, L_i: \mathcal{X} \times \mathcal{U} \times \mathcal{T} \rightarrow \mathbb{R}$

$$J(x, u, t) = \phi\left(x(t_f), t_f\right) + \sum_{i=1}^{n_L} \int_0^{t_f} L_i(x, u, \tau) d\tau$$

Find the optimal trajectory (x, u) over time τ that satisfies

$$u^* = \underset{u}{\operatorname{argmin}}\left(J(x, u, t)\right)$$

subject to constraints in C

RST Approach

NARI

<u>Dynamical System</u>

$$\mathcal{S}:\begin{cases}\dot{x}(t) = f(x(t),u(t),t)\\ y(t) = x(t)\end{cases}$$

<u>Constraints</u>

$$C = \{C_e, C_i\}$$
$$C_{e_i}(x,\dot{x},u,t) = 0$$
$$C_i(x,\dot{x},u,t) \le 0$$

<u>Performance Objectives</u>

$$J(x,u,t) = \phi\big(x(t_f),t_f\big) + \sum_{\boldsymbol{i=1}}^{\boldsymbol{n_L}} \int_0^{t_f} L_{\boldsymbol{i}}(x,u,\tau)d\tau$$

<u>Problem</u>

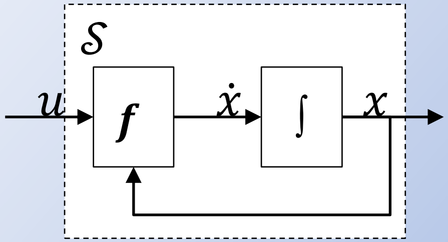
$$Find\ \ u^* = \underset{u}{\operatorname{argmin}}\big(J(x,u,t)\big)$$
subject to constraints in C

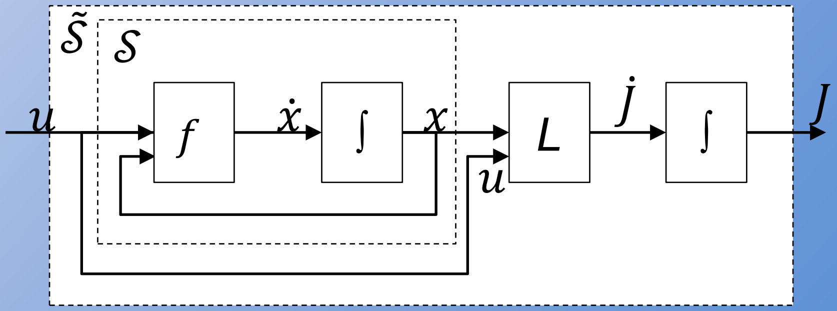
<u>Augmented System</u>

$$\tilde{\mathcal{S}}:\begin{cases}\dot{x}_{\tilde{\mathcal{S}}} = \begin{bmatrix}\dot{x}\\ \dot{J}'\end{bmatrix} = \begin{bmatrix} f(x,u,t)\\ \|L(x,u,t)\|_1\end{bmatrix}\\ y_{\tilde{\mathcal{S}}} = [J'] = [J'(t)]\end{cases}$$

<u>Augmented Problem</u>

$$Find\ \ u^* = \underset{u}{\operatorname{argmin}}\big(y_{\tilde{\mathcal{S}}}[0\colon t_f\colon x_0\colon u]\big)$$
subject to constraints in C





Subcomplement Systems

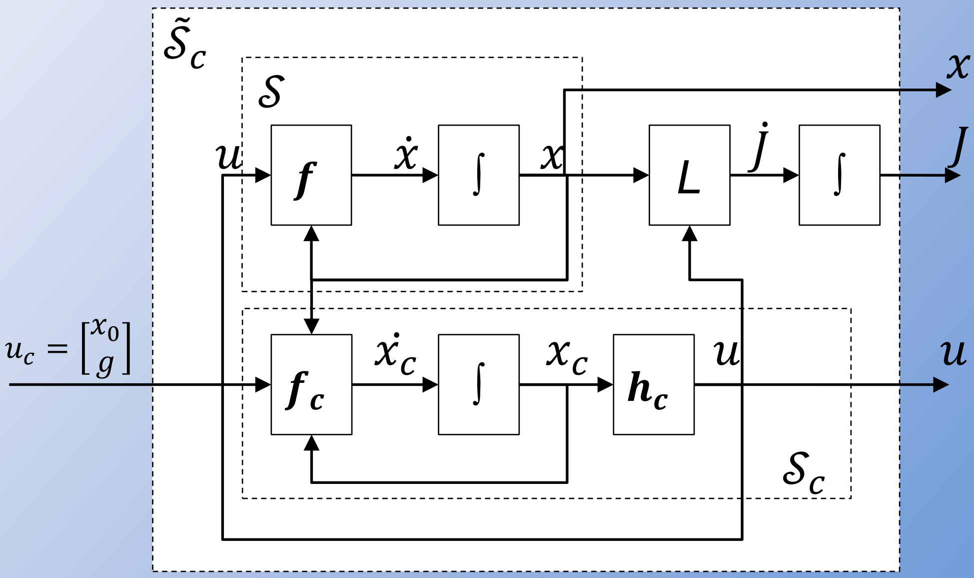
Subcomplement System

Define goal subspace $\mathcal{X}_G$, often $\mathcal{X}_G \subseteq \mathcal{X}$
Let $x_c \in \mathcal{X}_c$
Let $u_c \in \mathcal{U}_c = \mathcal{X} \times \mathcal{X}_G$
Let $y_c \in \mathcal{Y}_C = \mathcal{X} \times \mathcal{U} \times \mathbb{R}$
Define the subcomplement system to be

$$\mathcal{S}_c : \begin{cases} \dot{x_c} = [f_c(x_c, u_c, t)] \\ y_c = [u] = [h_c(x_c, u_c, t)] \end{cases}$$

Augmented Subcomplement System

$$\tilde{\mathcal{S}}_c : \begin{cases} \begin{bmatrix} \dot{x} \\ \dot{x_c} \\ \dot{\tilde{J}} \end{bmatrix} = \begin{bmatrix} f(x, u, t) \\ f_c(x_c, u_c, t) \\ \|L(x, u, t)\|_1 \end{bmatrix} \\ \begin{bmatrix} u \\ x \\ J \end{bmatrix} = \begin{bmatrix} h_c(x_c, u_c, t) \\ x \\ J \end{bmatrix} \end{cases}$$



Search Tree Algorithm

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- Let the search tree $\mathcal{T} = (V, E)$ be defined as a set of vertices $\mathcal{V} = (\mathcal{X}, \mathcal{U}, \mathcal{T}, \mathbb{R})$ where a vertex $v_i \in \mathcal{V}$ given by $v_i = (x(t_i), u(t_i), J(x_i, u_i, t_i), t_i)$, and edges $E =< V, V >$ be an ordered set of vertices

<u>Algorithm 1. BuildOptimizationTree (x_0, $\mathcal{G}$, C)</u>

Input: x_0: Start state, $\mathcal{G}$: Augmented subcomplement system, C: Constraint set, N: search depth

Variables: $\mathcal{T}$: Tree, (v, v_l, v*): Vertex (current, leaf, best)

1. $\mathcal{T} \leftarrow$ *InitTree*(x_0)
2. v*←∅
3. while (not *StopCondition*()) do
4. g←*RandomGoalPoint*()
5. v←*RandomTreeVertex*($\mathcal{T}$,g, C)
6. v_l←*GenerateBranch*($\mathcal{G}$, v, g, C)
7. v*←*StoreBestAtDepth*(v*,v_l,N)
8. End while

<u>Algorithm 2. GenerateBranch ($\mathcal{T}$, $\mathcal{G}$, v, g, C)</u>

Input: $\mathcal{T}$: Tree, $\mathcal{G}$: Start vertex, v: Start vertex, g: Goal vertex, C: Constraint set

Variables: Tree $\mathcal{T}$

Vertex v’

Branch b

1. b←FwdIntegrate ($\mathcal{G}$, v’, g)
2. b←*Trim*(b,C)
3. if (b ≠ ∅)
4. *TreeAdd* ($\mathcal{T}$, v, b)
5. End if

Many-Core Optimization

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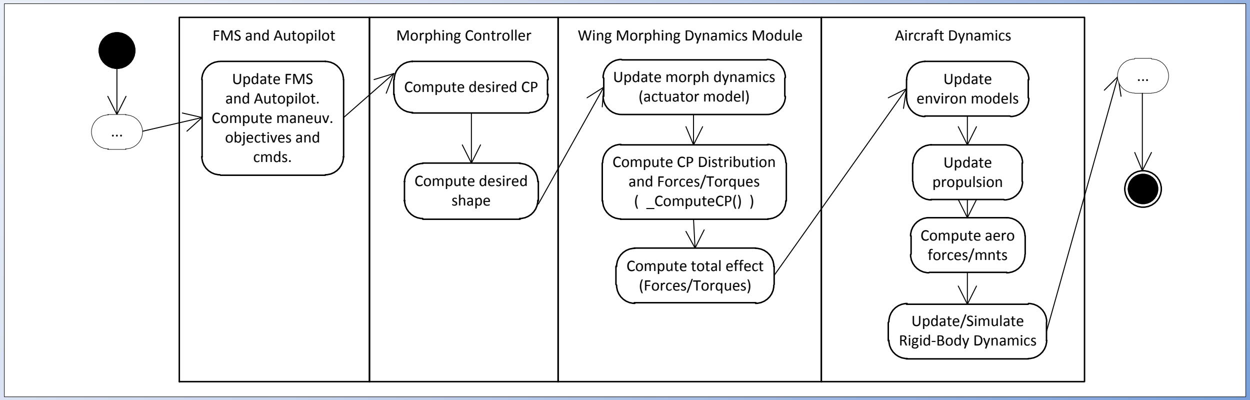
- Optimization study implemented vortex-panel solver on many-core hardware
- Target: NVIDIA Quadro FX 3700 GPU on Dell Precision M6400



Device 0	Quadro FX 3700M
CUDA Driver Version / Runtime Version	4.0 / 4.0
CUDA Capability Major/Minor version number:	1.1
Total amount of global memory:	966 MBytes (1013383168 bytes)
Number of Multiprocessors	16
CUDA Cores/MP	8
Number of CUDA Cores	128
GPU Clock Speed:	1.38 GHz
Memory Clock rate:	799.00 Mhz
Memory Bus Width:	256-bit
L2 Cache Size:	
Max Texture Dimension Size (x,y,z)	1D=(8192), 2D=(65536,32768), 3D=(2048,2048,2048)
Max Layered Texture Size (dim) x layers	1D=(8192) x 512, 2D=(8192,8192) x 512
Total amount of constant memory:	65536 bytes
Total amount of shared memory per block:	16384 bytes
Total number of registers available per block:	8192
Warp size:	32
Maximum number of threads per block:	512
Maximum sizes of each dimension of a block:	512 x 512 x 64
Maximum sizes of each dimension of a grid:	65535 x 65535 x 1
Maximum memory pitch:	2147483647 bytes

Many-Core Optimization

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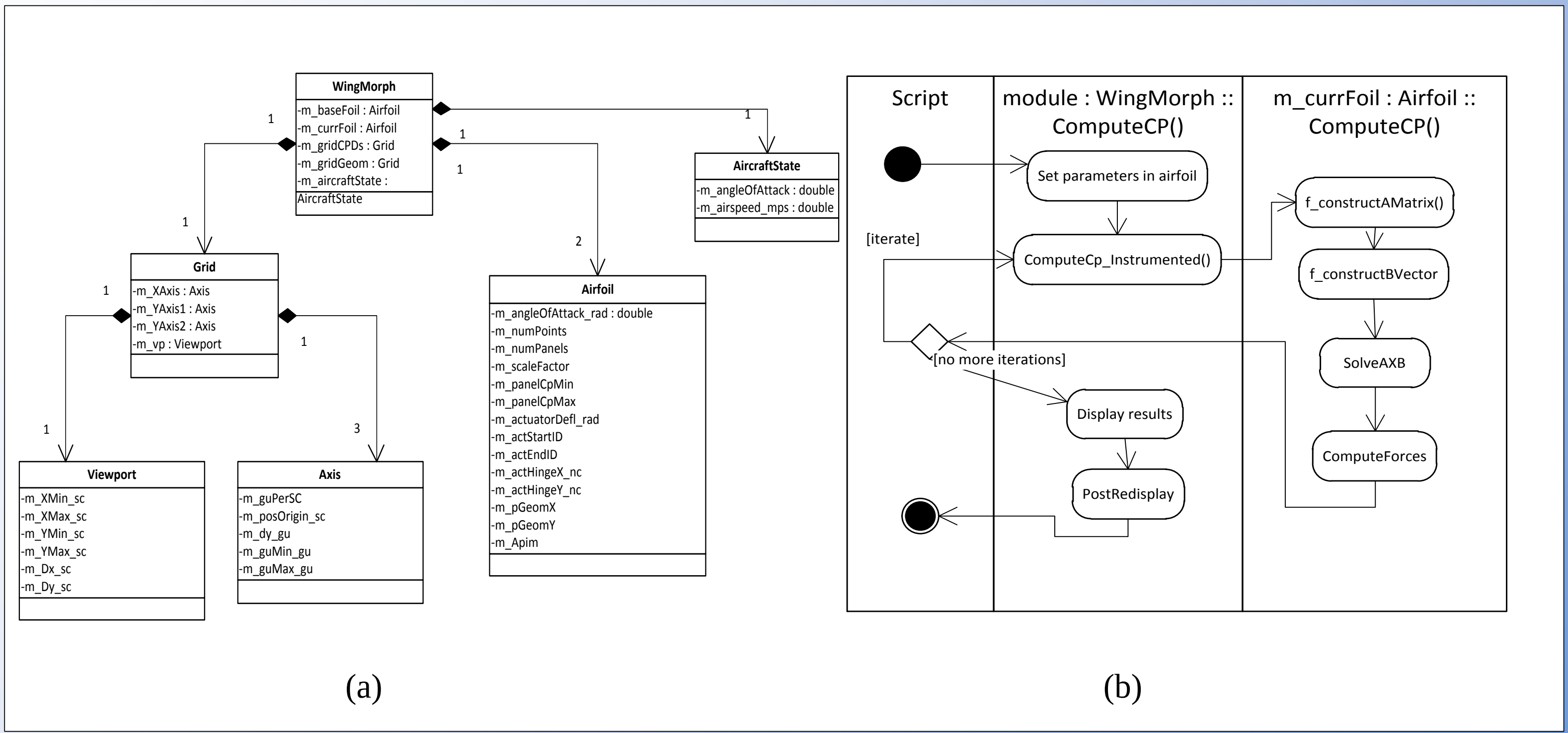


Class Structure (a) and Update Activity in WingMorph::ComputeCP and Airfoil::ComputeCP

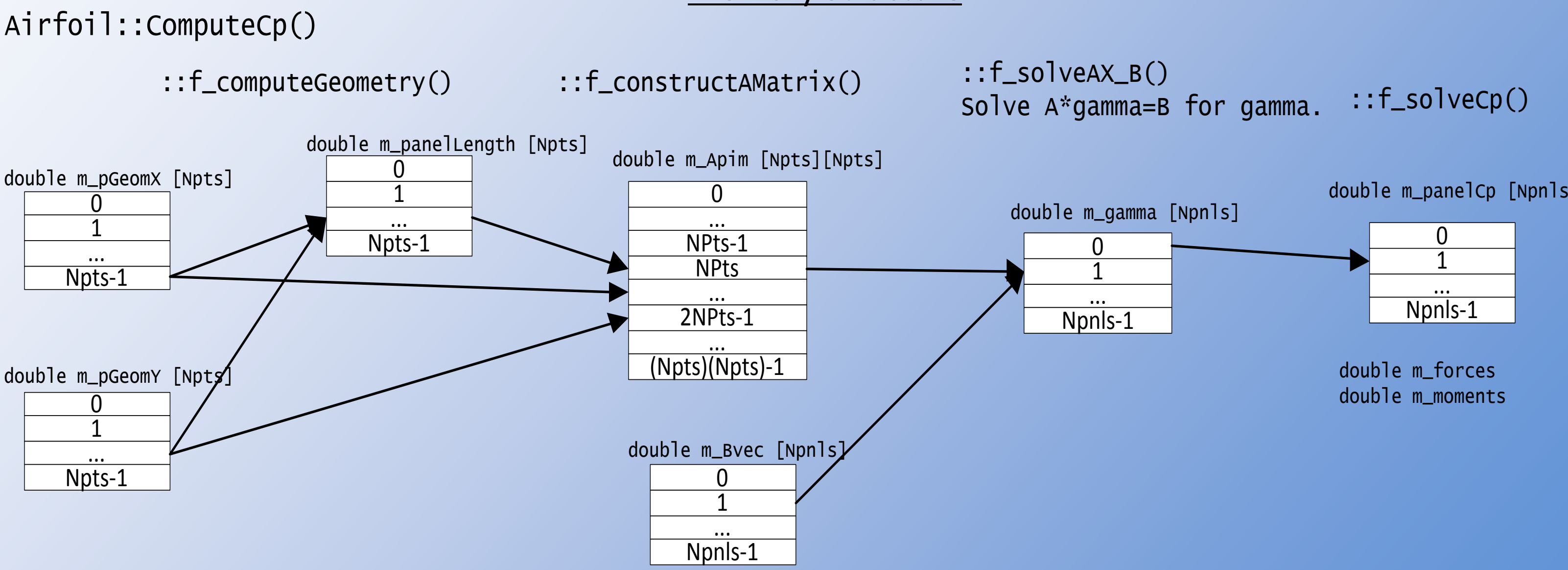
Many-Core Optimization

NARI

Table 1. Algorithm and Complexity

Step	Function	Description	Complexity
1	_ComputeGeometry()	Compute geometric arrays panelLength[], dX[], dY[]	O(N)
2	_ConstructAMatrix()	Construct A matrix and B vector. Baseline uses Gaussian Elimination	O(N^2)
3	_SolveAXB()	Solve Ax=b for x	O(N^3)
4	_SolveCP()	Solve for pressure distribution, sum total force and moment	O(N)

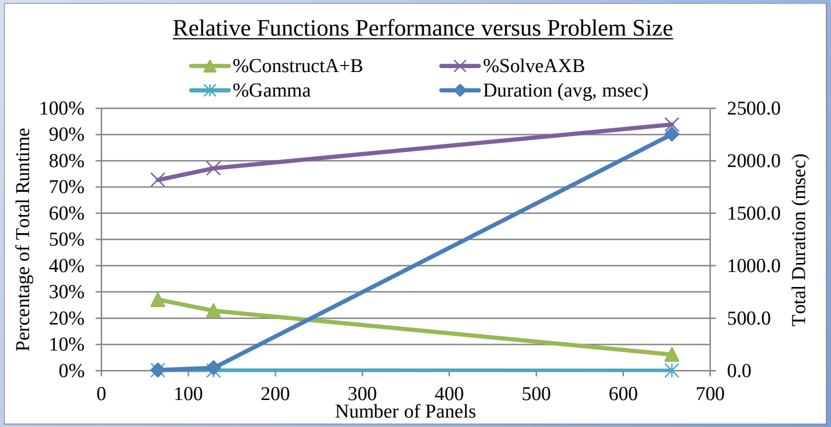
Memory Structure

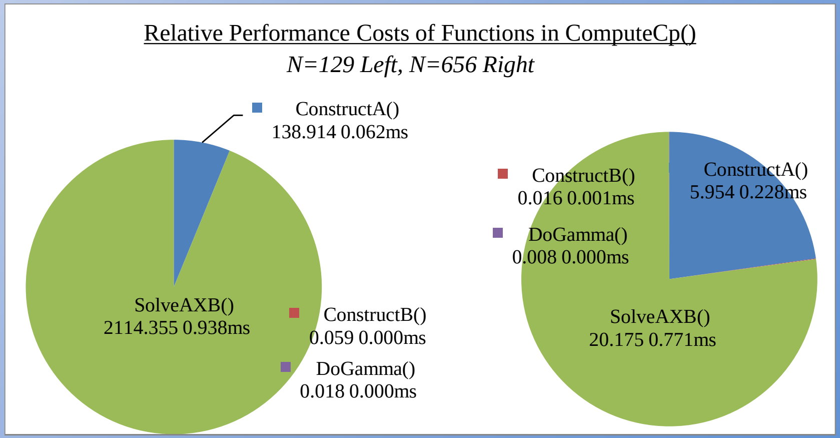


Many-Core Optimization

NARI

- Analyzed baseline performance as function of number of panels
- The template for each function is the same.
  1. Convert double arrays into floats
  2. Copy input vectors to device memory
  3. Perform kernel array operation
  4. Copy resulting device memory to float array in host memory
  5. Convert float array back to doubles
- The Ax=b operation was hand-coded using a Gaussian Elimination algorithm (not optimal for implementation)





Many-Core Optimization

NARI

- Initial optimization resulted in 35.5 times improvement on simple study
- Optimization focus in grey, cost for evaluating 200 airfoil sections with 656 panels each

Function (time in sec)	**Original**	**Opt A**	**Opt B**	**Opt C**	**Opt D**
(top)	6063.7	418.9	375.4	466.8	159.6
|ComputeCP	5389.7	437.6	470.1	379.2	185.0
|+ConstructA	231.2	27.1	14.7	10.2	10.9
|+ConstructB	0.1	0.0	0.0	0.0	0.0
|+SolveAXB	5569.6	485.8	455.1	429.6	157.1
|+ComputeGamma	38.3	0.0	0.0	0.0	0.0
Total	5657.2	418.9	375.4	466.8	159.6
Improvement (x original)		13.5	15.1	12.1	35.5
Time to 10 sections/50 panels	21.56	1.60	1.43	1.78	0.61

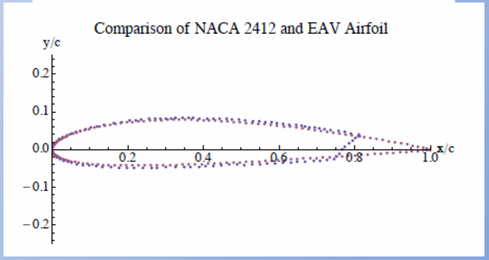
TECHNICAL DETAILS AND ACCOMPLISHMENTS

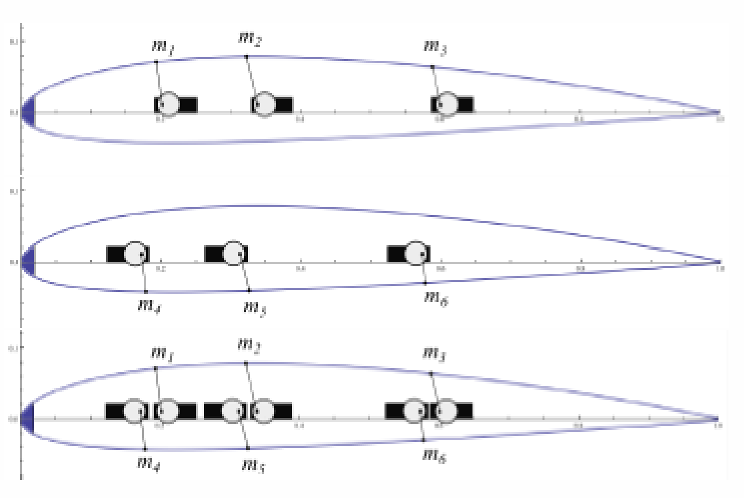
PART III – MORPHING WING STUDY

2D Morphing Wing Study

NARI

1. Developed morphing wing actuator prototype on a small NASA UAV
   - NASA EAV, a 1/4 scale Cessna 182
   - Intuitively placed servomotors and control points
2. Develop mathematical model of morphing wing actuator geometry, response and characteristics
   - Used NACA 2412 as baseline airfoil
   - Measured actuator speed and characteristics from prototype
   - Modeled using 6 control points
   - Top control points: 5-10% chord length
   - Bottom control points: 0-6% chord length
   - Used natural splines for interpolation between control points

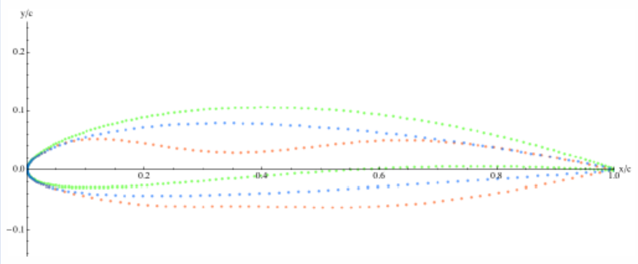




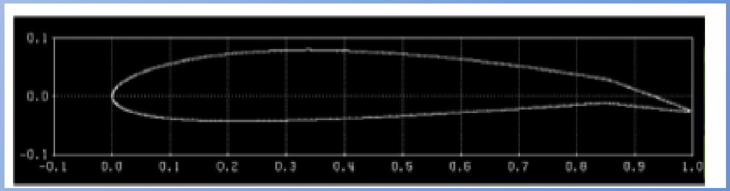
2D Morphing Wing Study

NARI

3. Generate database of performance versus actuator position for airfoil
   - Steady-state 2D analysis with X-FOIL
   - Stored resulting CL, CM, CD for each data point
   - Resulting database is highly nonlinear and non-convex over CL, CM, CD
   - Generated second database with X-FOIL control surface function



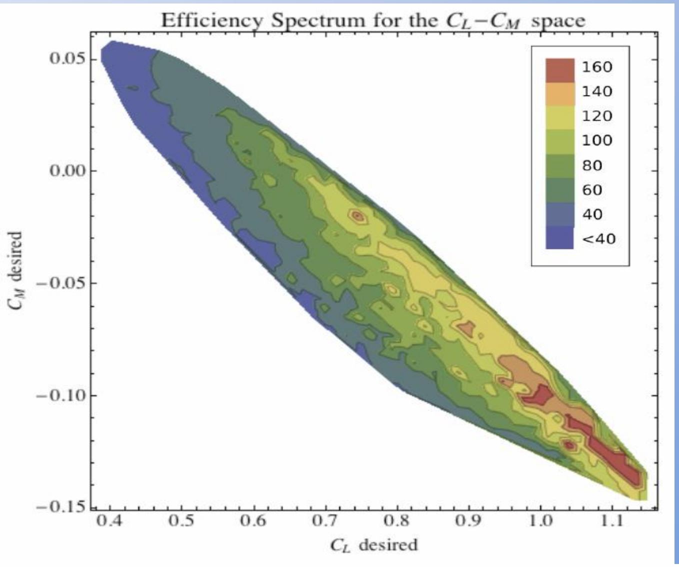
Parameter	Baseline/ Cruise Condition	Min	Max	Delta
Attack angle	5 deg	0 deg	15 deg	1 deg
Speed	20.5 m/s (40 knots)	-	-	-
m1		5%	10%	0.50%
m2		5%	10%	0.50%
m3		5%	10%	0.50%
m4		0%	6%	0.50%
m5		0%	6%	0.50%
m6		0%	6%	0.50%

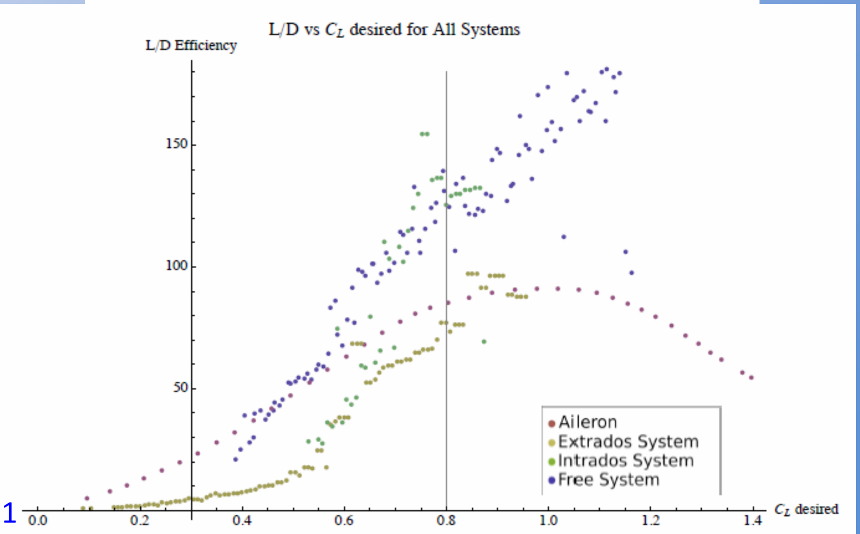


2D Morphing Wing Study

NARI

4. Analyze and optimize database
   - Find optimally L/D efficient mapping from desired (CL,CM) to an actuator vector solution u=(m1,..,m6)
   - Discretize CL-CM space into 100x100 buckets from CL=(0.4,1.15), CM=(-0.15,0.06)
   - Find most efficient actuator combination in each CL-CM bucket

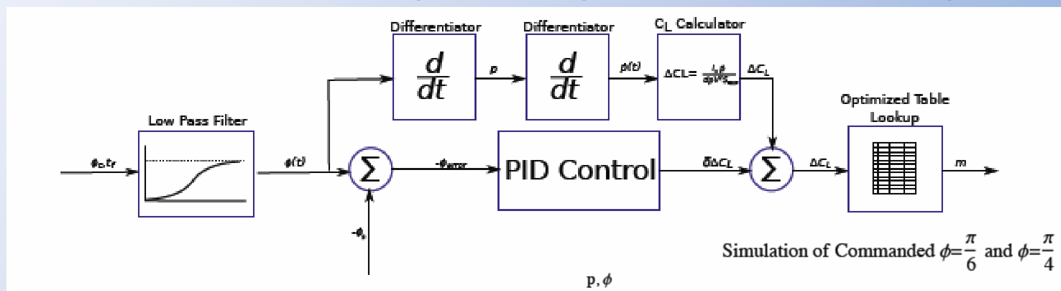




2D Morphing Wing Study

NARI

5. Design 2D controller to achieve roll angle using differential wing morphing



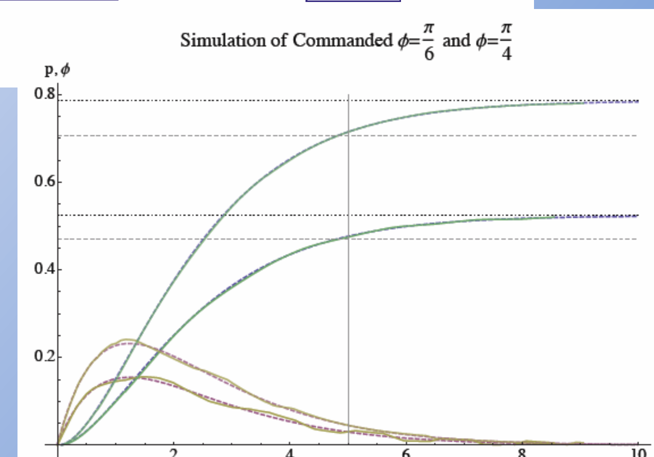
6. Test in simulation

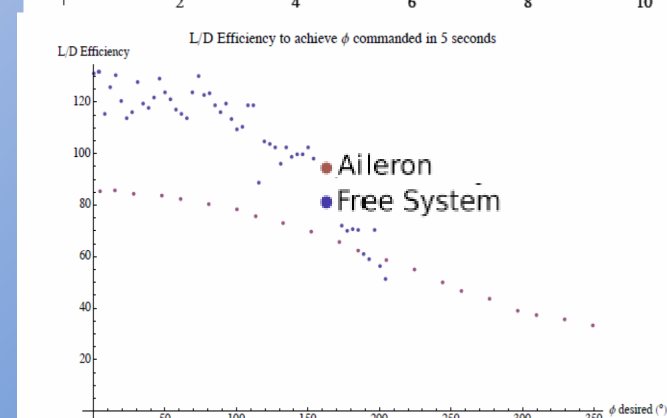
$$\dot{\bar{x}} = A\bar{x} + B\bar{u} + C. \qquad x = [v, p, r, \phi, u, w, q, \theta]$$

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} q_\infty S\cos(\beta)(-\cos(\alpha)(C_{D_L}+C_{D_R})+\sin(\alpha)(C_{L_R}+C_{L_L}) \\ q_\infty S\sin(\beta)(-\cos(\alpha)(C_{D_L}+C_{D_R})+\sin(\alpha)(C_{L_R}+C_{L_L}) \\ -q_\infty S(\sin(\alpha)(C_{D_L}+C_{D_R})+\cos(\alpha)(C_{L_L}+C_{L_R})) \end{pmatrix}$$

$$\begin{pmatrix} L \\ M \\ N \end{pmatrix} = \begin{pmatrix} 0 \\ d \\ 0 \end{pmatrix} \times \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_R + \begin{pmatrix} 0 \\ -d \\ 0 \end{pmatrix} \times \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_L + \begin{pmatrix} 0 \\ \frac{1}{2}q_\infty Sc(C_{M_L}+C_{M_R}) \\ 0 \end{pmatrix}$$

$$C = \begin{pmatrix} q_\infty S\sin(\beta)(-\cos(\alpha)(C_{D_L}+C_{D_R})+\sin(\alpha)(C_{L_L}+C_{L_R})) \\ dq_\infty S(\sin(\alpha)(C_{D_L}-C_{D_R})+\cos(\alpha)(C_{L_L}-C_{L_R})) \\ dq_\infty S\cos(\beta)(\cos(\alpha)(-C_{D_L}+C_{D_R})+\sin(\alpha)(C_{L_L}-C_{L_R})) \\ 0 \\ q_\infty S\cos(\beta)(-\cos(\alpha)(C_{D_L}+C_{D_R})+\sin(\alpha)(C_{L_L}+C_{L_R})) \\ -q_\infty S(\sin(\alpha)(C_{D_L}+C_{D_R})+\cos(\alpha)(C_{L_L}+C_{L_R})) \\ \frac{1}{2}cq_\infty S(C_{M_L}+C_{M_R}) \\ 0 \end{pmatrix}$$

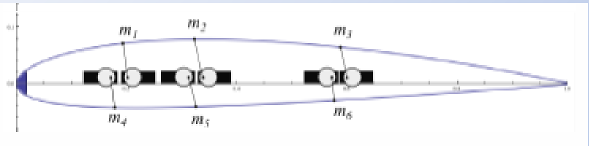




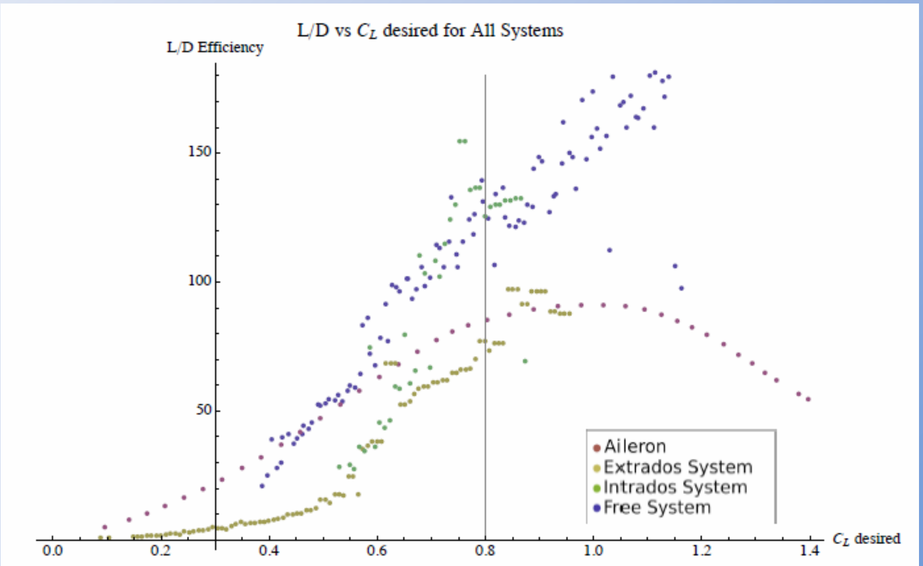
2D Morphing Wing Study

NARI

- Coarse 2D study investigated feasibility and expected benefits from concept
  - Real-time distributed individually-actuated control concept
  - Benefits expected to multiply with larger more complex systems



- Results show feasibility and expected L/D improvement
  - L/D improvement around ~41% across entire (flyable) range, 47% roll maneuvering efficiency improvement



PHASE 2 APPROACH AND PLAN

Summary of Approach and Phase 2 Plan

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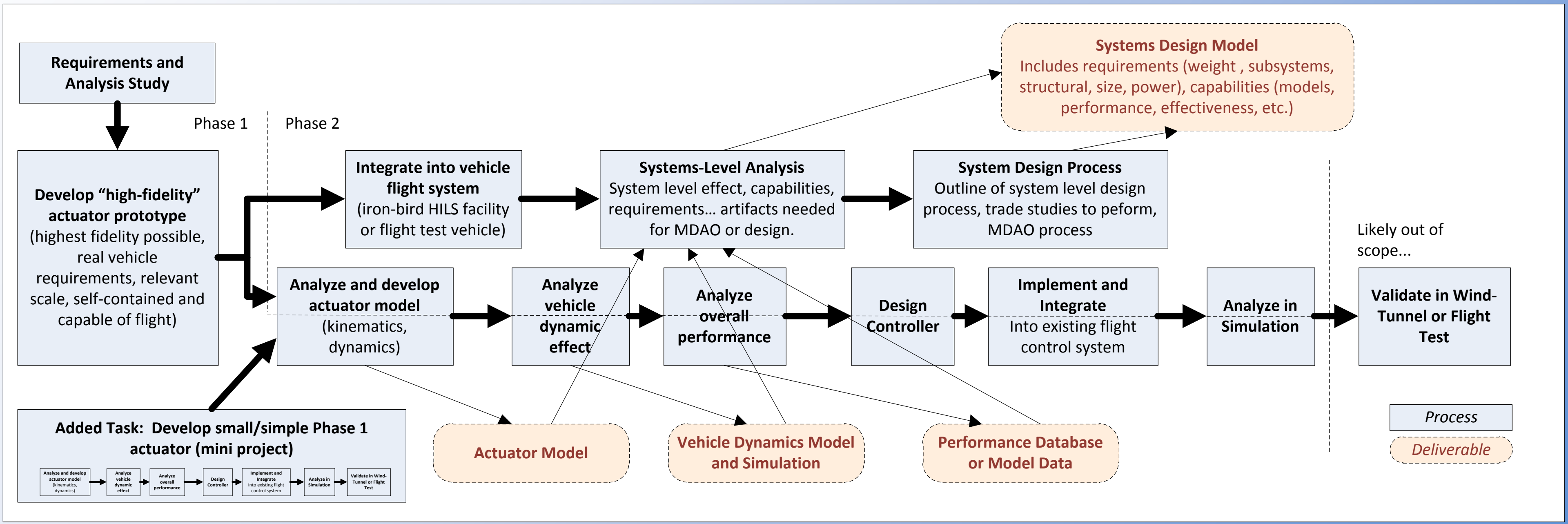

Phase 2 Schedule

NARI	Resources		2012						2013						2014					
Task	Lead	Support	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
PAWS Prototype Delivery, Analysis and Modeling																				
Complete PAWS prototype, deliver to NASA	KU	MLB																		
Develop structural kinematics model of the PAWS prototype actuator.	KU	NASA																		
Perform vehicle systems-level analysis and requirements	KU	NASA																		
Detail incorporation into MDAO process	KU	NASA																		
Submit prototype for external review from stakeholders - NASA and Boeing	KU, NASA																			
DMoWCs Control System Integration																				
Validate and Extend Model	NASA	UCSC																		
Integration DMoWCs and actuation model	NASA	UCSC																		
Develop distributed sensing and state estimation	NASA	UCSC																		
Conduct optimization and simulation performance studies	NASA	UCSC																		
DMoWCs and PAWS Integration and HILS Testing																				
Integrate PAWS prototype into the NASA Swift UAS iron-bird HILS facility.	NASA	MLB/CMU/UCSC																		
Install PAWS prototype and support hardware into the HILS facility.	NASA	CMU/UCSC																		
Integrate DMoWCs into HILS facility, showing closed-loop control of PAWS.	NASA	CMU/UCSC																		
Conduct integrated DMoWCs/PAWS hardware-in-the-loop simulation studies.	NASA	CMU/UCSC																		
Dissemination of Results																				
Conference Publications	All																			
Journal Submission	All																			

Phase 2 Proposed Plan Details

- PAWS Prototype Delivery, Analysis and Modeling
  - Complete PAWS prototype, deliver to NASA
  - Develop structural kinematics model of the PAWS prototype actuator
  - Perform vehicle systems-level analysis and requirements
  - Detail incorporation into MDAO process
  - Submit prototype for external review from stakeholders - NASA and Boeing
- DMoWCs Control System Integration
  - Validate and Extend Model
    - Conduct model validation and submit model for external review.
    - Investigate extending model to incorporate dynamic unsteady aerodynamics.
    - Deliverable: modeling library source-code and API
- Integration DMoWCs and actuation model
  - Integrate PAWS actuator model into DMoWCs simulation and control system.
  - DMoWCs components will be adapted for control of the PAWS actuation model.
- Develop distributed sensing and state estimation
  - Distributed estimation was demonstrated on a similar fluid/thermal model for building control. A similar approach will be used in this investigation.

Phase 2 Proposed Plan Details

NARI

- Conduct optimization and simulation performance studies
  - DMoWCs and PAWS Integration and HILS Testing (I&T)
    - Integrate PAWS prototype into the NASA Swift UAS iron-bird HILS facility.
    - Install PAWS prototype and support hardware into the HILS facility.
    - Integrate DMoWCs into HILS facility, showing closed-loop control of PAWS.
    - Conduct integrated DMoWCs/PAWS hardware-in-the-loop simulation studies.
- Flight Testing DMoWCs and PAWS: Optional Development Path
  - Perform integration of DMoWCs and PAWS
  - Conduct ground test and environment testing
  - Obtain flight permission from flight worthiness board
  - Conduct final flight tests
- Dissemination of Results
  - Fast dissemination of results through the following conference publications: 2012 AIAA Infotech conference (currently pending final review), 2013 AIAA Aerospace Sciences Meeting, 2013 IEEE Aerospace conference
  - Targeting submission to IEEE Trans. on Aerospace and Electronic Systems
  - Final NASA technical report

Phase 2 Information Dissemination Plan

- Fast dissemination of results through conference publications
  - 2012 AIAA Infotech conference (currently pending final review)
  - 2013 AIAA Aerospace Sciences Meeting
  - 2013 IEEE Aerospace conference
- Targeting submission to IEEE Trans. on Aerospace and Electronic Systems
- Final NASA technical report
- Project interaction with stakeholders
  - NASA Fixed-Wing (ESAC subtask), Boeing R&T unit, Cessna, MLB

Summary

NARI

- Phase 1 results showed concepts are feasible
- PAWS prototype on schedule to be completed at end of Phase 1
- NASA small-scale UAV prototype study shows feasibility and performance benefits
- Formalized decentralized control system framework and flight control system architecture
- Showed initial parallelization on many-core architecture
- Implemented model in simulation environment for testing in Phase 2
- Identified Phase 2 stakeholders and infusion plan into NASA ARMD research programs, identified technology commercialization partners (Boeing, Cessna, MLB)

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NARI

Integration and Control of Morphing Wing Structures for Fuel Efficiency/Performance

NARI's ARMD 2011 Phase 1 Seedling Fund Technical Seminar
June 5-7, 2012

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